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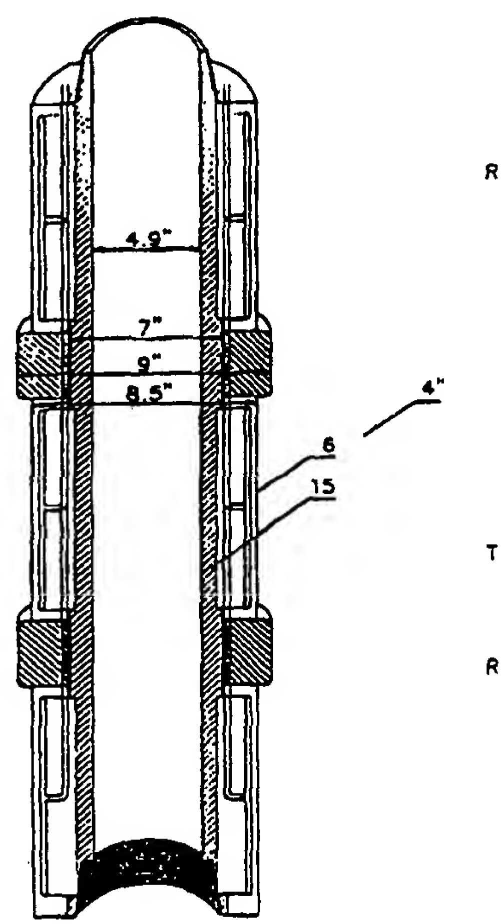
(57) Abstract

The invention is a well radar for detection of resistivity-horizons by reflection. The invention is applied in production zones in oil wells. A preferred embodiment of transmitter- and receiver-antennas is combined in a tubing string antenna module (4') which comprises a transmitter antenna group (2') with preferably two dipole tansmitter antennas (2) arranged on either side of the tubing string antenna module (4') by a first position along the tubing string antenna module (4'), a first directionally sensitive group (8') with preferably four dipole receiver antennas (8) arranged with even angular separation about the tubing string antenna module (4') by a second position along the tubing string antenna module (4'), a second directionally sensitive group (8') with preferably four dipole receiver antennas (8) arranged with even angular separation about the tubing string antenna module (4') by a third position along the tubing string antenna module (4'), preferably on the opposite side of the transmitter antenna group (2') with respect to the first directionally sensitive group (8').



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DEVICE FOR ELECTROMAGNETIC DETECTION OF GEOLOGICAL PROPERTIES IN A WELL.

Introduction

This invention concerns a radar-like device for use in production wells, and being arranged for detecting the oil/water contact in a reservoir rock.

More specifically the invention comprises a transmitter antenna for electromagnetic waves being arranged to be placed fixedly by a production tubing inside a geological formation, and receiver antennas, also arranged for being placed near a production tubing. This radar-like device is capable of detecting reflectors which are constituted by electrically conductive surfaces inside the reservoir. One such surface of particular importance is the oil/water contact, with the water front in most instances constituting a relatively sharp transition between oil-bearing sand with high resistivity, to water-filled sand with low resistivity, thereby consisting a reflector.

The technical background

Borehole logging tools utilising the radar principle is known from US 4.670. 717, US 4.814.768, US 4.297.699, US 4.430.653, and GB 2.030.414. Some of these patents use methods were one have to guess a wave propagation speed in order to be able to interpret the radar signals.

Schlumbergers US patent 5.530.359 "Borehole logging tools and methods using reflected electromagnetic signals" describes a logging tool with pulsed radar signals being transmitted from a transmitter antenna in a separate vertical section. The logging freely hangs in the borehole from a cable or in a coiled tubing. Linear antenna elements are applied being arranged parallelly with the tool's long axis z. Electromagnetic pulses are emitted with the centre frequency of 40 MHz and with a highest frequency components of 120 MHz. This pulse is radiated in all directions in the formation and is reflected by structures in the formation back to the tool in the borehole. The transit time for the pulse out to the structure and back to the tool is used for determining the distance between the reflecting structure and the borehole. Directional information is achieved by

having arranged receiver antennas about the entire periphery of the tool so that the reflecting structure's direction may be found by taking differences between the reflected signals. These differences may be calculated by means of electronic circuits, or subtraction may be performed by directly differentially coupled receiver antennas. One method for calculating the reflected signals directions is given. One disadvantage with Schlumberger's patent 5.530.359 is that the instrument applies pulsed electromagnetic waves. This entails spreading of frequency components already in the emitted signal, and thereby the emitted signal pulse has a continuously varying group velocity. The reflected signal becomes smeared out and one gas an unclear image of the reflecting structures. Close reflecting structures will also dominate over the more remotely reflecting structures, so that the more remote structures very difficulty may be detected if the closer rocks has relatively high conductivity/low resistivity. Another disadvantage by the Schlumberger instrument is that it is not fixedly arranged by the geological formation, so that there are no possibilities for tracing changes of the electrical parameters in the formation over a period of time, e.g. from one date to another. The instrument is also not arranged for being applied in production wells or in injection wells.

Another apparatus is described in US patent 5.552.786: "Method and apparatus for logging underground formations using radar", (Schlumberger). US patent 5.552.786 describes a logging tool which partially solves the problem with the electromagnetic wave speed in the formations which are to be logged. The apparatus transmits an electromagnetic pulse in close contact with borehole wall, into the formations and receives the direct wave in a predetermined distance along the borehole string from the transmitter. Thus the wave speed for the direct wave through the rocks (which may be invaded by borehole mud) becomes calculated and the reflector's distances from the transmitter/receiver system may be calculated more exactly than if one had only an estimate of the wave speed.

US patent 4.504.833 "Synthetic pulse radar system and method" describes a synthetically pulsed radar generating a

plurality of signals of different frequency simultaneously. The response from the underground on those different frequencies simulates parts of the Fourier spectrum which would have been measured if one emitted a very short pulse which, according to the mathematical background, should be very broad in frequency spectrum. The system is however arranged for among other things to be used on board a vehicle because it according to its claim 1 shall be able to generate all the component signals simultaneously.

US patent 4.275.787 "Method for monitoring subsurface combustion and gasification processes in coal seams" describes a radar for detection of a combustion front in a geological formation, for example a coal bearing formation. Because of resistivity generally increases with temperature such a combustion front will display high resistivity and constitute a very large contrast with respect to the coal bearing formation which normally will display low resistivity. The attenuation exceeds 100 dB/wave length in the combustion front, and the attenuation in "Pittsburgh coal" is one dB/wave length, for "British coal" the attenuation is 3 dB/wave length. The applicant mentions that a detection range of the combustion front is 100 metres, an unrealistically large distance when one takes in consideration the conditions in an oil well with the attenuation of the signal being much higher and where it is a very difficult task to detect reflecting surfaces only one to two metres out in the reservoir. A swept signal varying continuously between a lowest and a highest frequency is emitted. Whereas the combustion front is displaced one will by subtraction of the received signals be able to see a change in the difference signal between the observations. However, that patent does not consider the need for tuning of the transmitter antennas when the transmitter antennas are situated very closely, e.g. a few millimetres from a metallic tubing surface (e.g. the linear tubing or a completion tubing) and the frequency of the emitted signal shall be changed.

Statement of problem: expected electrical properties on the background of logs.

The invention is made partially on the background of the potential problems which could arise in connection with petroleum production on the Troll oilfield in the North Sea. Below will be described how the resistivities in the actual geological formations are relatively lower with respect to the conditions being described in the known art, and where it thus will not be feasible to perform detection by means of electromagnetic waves according by using the known art.

Expected resistivity.

A map of the Troll Oilfield generally covering the licence blocks 31/2, 31/3, 31/5 and 31/6 are shown in Fig. 3a. Resistivity data are available from five wells: 31/2-2 (Fig. 3b), 31/2-4 (Fig. 3c), 31/2-5 (Fig. 3d), 31/2-6 (Fig. 3e), and 31/2-7 (Fig. 3f). The graphs display resistivity in Ωm as a function of logging depth in generally vertical wells through the reservoir rocks. The oil/water contact, hereafter called "OWC" is defined in the wells by the depths being marked in the respective graphs. The distribution of resistivity with respect to depth is markedly different from well to well. In 31/2-2 the resistivity R varies between about 3 Ωm and 1 3 Ωm over the OWC while R in well 31/2-4 decreases from 100 Ωm to 1 Ωm over the OWC. In well 31/2-5 the resistivity varies between 40 Ωm and 80 Ωm before it starts to decrease monotonously, about 1 metre above the OWC. By the OWC the resistivity falls by about 7 Ωm. The development in well 31/2-6 is characterized by a relatively strong "ripple" between 8 Ωm and 14 Ωm, even though the resistivity drop is clear by the OWC. Well 31/2-7 has a low and relatively little varying R in the area between 7 metres above the OWC and down to the OWC, with a maximum of 2 Ωm and is evenly falling to 0.4 Ωm just before the OWC.

The resistivity curves show that local variations in R may be much larger than the drop in R that takes place at the OWC. Because the conductivity of the formations generally arises from saline water in the pore spaces or conductive schists, local variations may be due to varying reservoir quality in the form of a combination of clay mineral content and porosity. Parameters like local

lithology, texture, facies and overpressure will also affect the resistivity. Resistivity tools are generally quite precise and give repeatable measurements. Generally the depth resolution is small, about 10 cm per measurement point, and the logs are smoothed to a certain degree by the contact assembly of the instrument, so the local formation resistivity will vary more than shown by the logs.

Expected dielectric.

No dielectrical logs are available from the Troll Oilfield. Here, dielectrical data are applied based on estimates of the known dielectrical properties in sandstone, oil and water. We select ε_{rock} =7. When δ is 0.20 (20% porosity) ε_{ro} equals 5.82, showing that ε_{ro}= 6 is a reasonable estimate of the dielectric constant for oil saturated sandstone.

The relative dielectric constant for sea water, ε_{water} =80 (King & Smith, 1981) by the frequencies which are actual to apply in connection with this invention. The dielectrical constant in water saturated sandstone is ε_{rw} =13. Figs. 4a, b, c, d, and e display estimated distributions of relative dielectrical values based on the water saturation in a 5 metres transition zone over the OWC in the same wells as for Figs. 3b-f. The scale indicating the relative dielectric constant is from about 6 to about 13.

Wave propagation in a conductive transition zone.

Fig. 5a displays an attenuation graph for electromagnetic waves in the frequency range between 1 MHz and 200 MHz. ε_r =6 and the resistivity R_{DC} is varied in steps of 5 Ωm from 5 Ωm to 30 Ωm. The higher the resistivity is, the more "transparent" the rocks become to electromagnetic radiation.

Fig. 5b with the same frequency range displays graphs for constant R_{DC} =30 Ωm and with ε_r varies from 6, 8, 10, 12, 14, to 16. One can see that the dielectric constant has less effect on the attenuation than the resistivity. The graphs show that the attenuation is more than 10 dB/m for 30 Ωm and frequencies above 12 MHz. Above 10 dB/m attenuation gives more than 100 dB attenuation on return from a reflector at a

distance of 5 metres.

Fig. 5c displays a section of the frequency range from Fig. 5a, between 1 and 16 MHz. The attenuation is still high for resistivities below 10 Ωm even in this low frequency range. Fig. 5d displays the waves phase velocities as a function of frequency between 1 and 16 MHz. Thus, on the background of the attenuation, the frequencies applied in a preferred embodiment of the invention may be between 1 and 16 MHz. Within this frequency range the phase velocity varies strongly with the resistivity which may give strong dispersion of an electromagnetic signal with a broad frequency content.

Reflection, backscattering.

All horizons with electromagnetic resistivity contrast in the well will result in reflections. Particles with higher conductivity, e.g. metal oxides, will entail a dispersion of the electromagnetic waves. Near horizons will become detected more strongly than remote horizons given that the resistivity contrasts being equal, due to approximately spherically geometric spreading. This means that the reflexes from the resistivity contrast by the OWC may be masked behind a large number of strong reflexes from local resistivity contrasts in the sandstone in the oil zone over the OWC. As an example, the resistivity contrasts represented by the gradients of R at 1578 metres and at 1580,5 metres depth in Fig. 3e will give strong reflexes which initially are not different from the reflex at the OWC.

The purpose of the invention.

One purpose of this invention is to provide a system to measure the depth of the oil/water or the gas/water contact in a petroleum reservoir by means of electromagnetic waves.

Another purpose is to provide an instrument arranged for registering and mapping the distribution of resistivity in the petroleum reservoir around the well, to apply this resistivity in geological interpretations of the reservoir.

Definition of the invention; refer nce to the claims.

The above mentioned problems are remedied by means of the present invention being a device for radar detection in a well in a geological formation. The new and inventive by the invention is:

(a) at least one transmitter antenna for emission of electromagnetic waves, mounted by a tubing string, and being arranged for fixed mounting with respect to the geological formation, and

(b) at least one, preferably more receiver antennas for reflected electromagnetic waves, by preferably the same tubing string, also being arranged for fixed mounting with respect to the geological formation.

Additional features of the invention are given by the dependent claims.

Description of the drawings.

The invention will in the following paragraphs be described in detail with non-limiting examples of preferred embodiments of the invention, with reference to the accompanying drawing figures of the non-limiting examples, with:

Fig. 1 illustrating a part of a production well with production tubing in a geological production zone for petroleum fluids, with oil and gas being above of the production zone, and water below.

Fig. 2 illustrates schematically an embodiment the invention arranged by a production tubing.

Fig. 3 displays a map over licence blocks of the Troll Oilfield of the North Sea, and Figs. 3b, c, d, e, and f display logs of resistivity as a function of depth in five vertical boreholes in the Troll Oilfield.

Figs. 4a, b, c, d, and e display estimated distributions of relative dielectrical values based on water saturation in a 5 metres transition zone across the OWC in the same wells Figs. 3b-f. The scales have 13 as the maximum value, indicating complete water saturation of a 20% porous rock.

Fig. 5a display theoretical graphs of electromagnetic waves' attenuation as a function of frequencies between 1 MHz and 200 MHz, for rocks with varying conductivity or

resistivity.

Fig. 5b display theoretical graphs of electromagnetic waves' attenuation as a function of frequencies between 1 MHz and 200 MHz, for rocks having varying dielectrical constant.

Fig. 5c display the same as Fig. 5a, but limited to a frequency range between 1 and 16 MHz.

Fig. 5d display theoretical graphs of phase velocity as a function of frequencies between 1 and 16 MHz.

Fig. 6a display a section of a preferred embodiment of the invention with a module comprising transmitter- and receiver antennas and which may enter as an ordinary threaded part of the completion in the production zone.

Fig. 6b displays in perspective view the module of Fig. 6a, with outer conical threading in the top, and correspondingly with inner conical threading in the lower part.

Fig. 7 is a diagram of components that may enter into an electronics package arranged at each particular module, arranged for, among other things, energy supply, control of transmitter- and receiver antennas, signal processing and communication.

Fig. 8 displays an application of a preferred embodiment of the invention for detection of change of the distance between the radar and several sections of an oil/water contact OWC.

Fig. 9 is a larger perspective view of a well with corresponding surface arrangement, with the well comprising transmitter- and receiver antennas in a horizontal production zone with varying distance to the oil/water contact OWC.

Detailed description of the invention.

The well.

Fig. 1 displays a production well or a borehole 1 in a geological formation, which may be on land or likely below the sea bottom. Usually there will be inserted a steel casing in several sections in the drilled hol , from the seabed and down to the top of the formation producing petroleum fluids as oil or natural gas. The producing

formation may be without a liner pipe, a so-called open completion, or have a liner pipe of a composite material being transparent to electromagnetic waves. In a preferred embodiment of this invention there will not be inserted a liner tube in the production zone, but there will be performed a cementing of a production tubing in the well 1. The geological formation will in this context comprise a reservoir rock, e.g. a porous, permeable sandstone formation 9. The borehole 1 may be more or less deviation drilled and is in the figure shown as a nearly horizontal borehole 1 even though the invention may be applied in boreholes with all deviation angles from the vertical downwards direction between 0 and 180 degrees. A production tubing 4 is arranged for completion of the production well or the borehole. The production tubing's 4 diameter may be 7" in an 8 1/2" borehole 1. A liner pipe (not shown) is usually arranged outside the production tubing 4. The liner pipe may be cemented and perforated, or consist of a fine mesh retaining sand and letting oil, gas and water through. A preferred embodiment of the invention will be applied in a nearly horizontally drilled production well in a sandstone formation 9. An oil/water contact OWC constitutes the limit between the essentially oil-saturated sandstone 5 and water-saturated sandstone 7. This invention may also be applied in an injection well or in an observation well.

The device according to the invention.

At least one transmitter antenna 2 for emission of electromagnetic waves is fixedly arranged by the tubing string 4. The transmitter antenna 2 is arranged for fixed mounting with respect to the geological formation, and is, in electrical terms, not shielded with respect to the geological formations, and arranged for being permanently located in the well. One or more receiver antennas 8 for electromagnetic waves is also arranged by the tubing string 4. The receiver antennas 8 are also arranged for fixed mounting with respect to the geological formation, and are, in electrical terms, unshielded with respect to the geological formations, and arranged for being permanently located in the well. The purp se of the fixed arrangement in

the production zone is that measurements may be performed with some time interval if it is difficult to detect horizons by means of pulsed radar measurements. If the OWC has displaced itself during the interval between measurements, one may by means of subtraction of the measurements detect the actual change, and estimate the position of the OWC.

The radar in the well.

Fig. 2 displays a principle illustration of a possible embodiment of the invention, with transmitter antennas 2 and receiver antennas 8 arranged near a production tubing 4. If the production tubing 4 is metallic and electrically conductive, being the actual situation, the antennas 2 and 8 must be arranged in the annulus between the production tubing 4 and the geological formation 9. In a preferred embodiment of the invention the antennas 2 and 8 will be cemented in the annulus in the production zone in the formation 9, so that they are absolutely fixed in position and orientation. This absolute fixation of position and orientation gives measurement- and analysis advantages which are not found in the known art.

The fixed arrangement may be performed in several ways: the antenna may be fixedly arranged outside of the tubing string 4, and cemented to the formation by means of cement. In one preferred embodiment of the invention shown in Fig. 6b, transmitter antennas 2 and receiver antennas 8 are arranged in unitary tubing string modules 4' which may be screw-threadedly joined and working as ordinary components in a tubing string 4 in a production well completion.

A preferred embodiment according to this invention will be applied in an approximately horizontal well 1 in a geological formation 9 as shown in Fig. 1. Fig. 2 displays an arrangement for detection of electrical properties comprising at least one transmitter antenna 2 for emission of electromagnetic waves 26, mounted by a tubing string 4, with the transmitter antenna 2 being arranged for fixed mounting with respect to the geological formation 9, at least one, preferably more receiver antennas 8 for the reflected electromagnetic waves 26, by preferably the same

tubing string 4, with the receiver antennas 8 being arranged for fixed mounting with respect to the geological formation 9. The receiver antennas 8 must be arranged so close to the transmitter antennas 2 that they under the prevailing surrounding resistivities may receive reflected electromagnetic waves. The antennas' fixed position by the geological formation will normally take place by cementing, which leads to a halt of possibly existing fluid flow between the antenna and the formation, and that any possible wellstream thus must take place inside the well tubing. By bringing the wellstream between the antenna and the geological formation to a halt, changing electromagnetic properties of the fluid in the wellstream will not be able to disturb the emitted or received electromagnetic signals. In Fig. 2 (and 8) it is, due to the legibility, not indicated that the antenna and the tube may be entirely or partially cemented in along the well.

A directionally sensitive group 8' comprising three or more receiver antennas 8 are in a preferred embodiment arranged around the axis of the tubing string 4 and essentially by the same position along the tubing string 4, arranged to detect the reflected electromagnetic waves' 26 and their reflectors' direction with respect to the tubing string's 4 axis. Such directionally sensitive antenna groups 8 are displayed as two groups of dipole antennas 8, with one antenna group 8' arranged on either side of the displayed transmitter antenna 2. In this manner, reflected electromagnetic waves received by several receiver antennas 8 by each particular antenna group 8' may be combined in order to calculate a direction α for the reflector in the plane P having the tubing string's 4 axis through the antenna group as its normal line. This is illustrated in Fig. 2. The combination of signals may take place through physical coupling of antenna signals to achieve differences, or combinations may be performed digitally after registering the waves. Phase differences between the incoming signals may also be utilized to find the angle α. An angle β with respect to the normal plane P may be calculated by combining reflected electromagnetic signals received on at least two receiver antennas 8 arranged with each their distance from

the transmitter antenna, as counted along the tubing string 4, and preferably on either side of the transmitter antenna 2. The angles α and β determine uniquely the direction of a reflector. A reflector's distance may be determined by estimating two-way travel time for an electromagnetic pulse. In this way a reflector's position be calculated with respect to the tubing string 4 and its transmitter antennas 2 and receiver antennas 8.

In the same way, it is advantageous having an embodiment with a transmitter antenna group 2' comprising two or more transmitter antennas 2 arranged about the tubing string's 4 axis and essentially by the same position along the tubing string 4, arranged for emitting electromagnetic waves generally in a selected direction with respect to the tubing string's 4 axis.

Fig. 6a displays a preferred embodiment of the invention is transmitter antennas 2 and receiver antennas 8 combined in one tubing string antenna module 4' comprising a transmitter antenna group 2' having at least two transmitter antennas 2 arranged at a first position along the tubing string antenna module 4', and at least one directionally sensitive group 8' having at least three receiver antennas 8 arranged at a second position along the tubing string antenna module 4'. In the most preferred embodiment of the tubing string antenna module 4' it comprises a transmitter antenna group 2' having preferably two dipole transmitter antennas 2 arranged on either sides of the tubing string 4 at a first position along the tubing string antenna module 4', a first directionally sensitive group 8' having preferably four dipole-receiver antennas 8 arranged with even angular separation about the tubing string 4 at a second position along the tubing string antenna module 4', and a second directionally sensitive group 8' having preferably four dipole-receiver antennas 8 arranged in the same way at a third position along the tubing string antenna module 4', preferably on at the opposite side of the transmitter antenna group 2' with respect to the first directionally sensitive group 8'.

Fig. 6b displays a perspective illustration of the tubing string antenna module 4'. The inner dimension in the

preferred embodiment is 4.9" and the metallic tube 15 will have a diameter of 7". Ceramic isolators 6 are arranged on the outside of the metallic surface of the tube 15. The ceramic isolators 6 constitute a basis for respectively transmitter antennas 2 and receiver antennas 8. In a preferred embodiment the isolators may be recessed into a cylinder-shaped recess in the metallic tube 15. The entire side surface of the tubing string antenna module 8' [4'] is covered by a non-conductive jacket in order to DC-isolate the electrical equipment from the well 1 and the geological formation 9. Centralizing devices are also arranged on the outer surface of each tubing string antenna module 4'. In a preferred embodiment of each centralizer is 9". This does not exclude other dimensions for the tubing string antenna module 4'. Electrical conductors 7 are arranged for energy supply and communication along the tubing string antenna module 4', with means for electrical coupling between two or more tubing string antenna modules 4' internally and also equipment other where, e.g. on at the surface.

The tubing string antenna module 4' will normally constitute a part of a series of equal modules 4', together with other modular parts of a production tubing in a well completion string. The tubing string antenna module is arranged preferably to be fixedly cemented in the well. The module 4' and the electrical conductors 7 must med marked, e.g. magnetically , in order not to be shot to pieces during perforation of the production tubing.

An electronics package 20 comprising necessary equipment to run the radar consists of a signal generator 22 for generation of electromagnetic signals 25 to the transmitter antenna 2, devices 80 for reception of signals ($85_1, 85_2, \ldots, 85_n$) induced in each of the receiver antennas ($8_1, 8_2, \ldots, 8_n$), signal processing means 82 for processing of the received signals ($85_1, 85_2, \ldots, 85_n$), and communication- and control devices 100 for transmission of signals 105 representing the electrical signals ($85_1, 85_2, \ldots, 85_n$), and for reception of control signals 205. Th contr l signals 205 and energy supply may in a preferred embodiment take place from a communication device 200 by the surface, via the electrical conductors 7.

In a preferred embodiment of the invention the electronics package 20 is situated in the immediate vicinity of the antennas 2, 8. In an additionally preferred embodiment illustrated in the diagram of Fig. 7, the tubing string antenna module 4' comprises the electronics package 20, and the electronics package 20 also comprises an address unit 55, an accumulator- and charging unit 56, a memory 54 and a rest mode unit 57. The signal processing means 82 may be arranged for downhole processing of measured data. In the preferred embodiment each tubing string antenna module 4' will be addressable and selectively activated from the communication device 200. The accumulator- and charging device 56 may accumulate energy sufficiently so that sufficient energy may be emitted into the geological formations from the transmitter antennas 2 in order for the receiver antennas 8 to be able to register signals from reflectors. Due to power limitations on the energy- and communication conductors 7 the rest mode unit 57 is applied to activate different addressable electronics packages 20 with corresponding antennas 2, 8 each in their turn, both with respect to charging, emission and processing.

In a preferred embodiment the signal generator 22 for generation of electromagnetic signals 25 to the transmitter antenna 2 will be arranged for generation of coherent continuous electromagnetic waves 26 from the transmitter antenna 2. Thus one may avoid dispersion of emitted electromagnetic signals due to varying group velocity as a function of the frequency. In an additionally preferred embodiment the signal generator 22 is arranged for generation of electrical signals 25 to the transmitter antenna 2 for emission of coherent continuous electromagnetic waves by a number of *i* different frequencies $f_1, f_2, \ldots, f_i$ from the transmitter antenna 2.

An impedance adjustment device 23 (not shown) arranged for adjusting the transmitter antennas impedance to maximal energy emission to the geological formation 9 at each particular of the discretely emitted frequencies $f_1, f_2, \ldots, f_i$ is needed. This impedance adjustment device 23 may be electronic switches in the dipole antennas 2 themselves. The electronic switches adjust the dipole

antennas' physical length. Alternatively, or as a supplement to switches on the antennas, a tuning of the resonance circuits' capacitance by feedback may be performed.

In a corresponding way there is, in the preferred embodiment, arranged an impedance adjustment device 83 (not shown) arranged for adapting the receiver antenna's 8 impedance to each particular of the emitted discrete frequencies f_1, f_2, ..., f_i . Thus the transmitter antennas 2 and the receiver antennas with corresponding impedance adjustment device 23, 83 have very similar construction designs.

In order to avoid direct coupling between the transmitter antenna 2 and the receiver antenna 8 there may be arranged cancelling devices 28 arranged for cancelling of direct waves or directly coupled signals between the transmitter antenna 2 and the receiver antenna 8. Differential coupling between receiver antennas 8, possibly an attenuated differential coupling between a part of the voltage signal 25 to the transmitter antenna 2 and the receiver antenna 8 is a possible solution to cancel the emitted signal from the receiver antenna 8, especially by emission of coherent continuous electromagnetic waves 26. By emission of pulsed signals cancelling of direct waves or directly coupled signals between the transmitter antenna 2 may be performed by means of delayed sampling on at the receiver antenna 8 until the direct wave has passed.

The control device 200 may be situated preferably on at the sea bottom or the earth's surface, or on at any other place.

The signal processing devices 82 for processing of the received signals (85_1,85_2,.., 85_n) comprises circuits or means arranged for forming at least one discrete Fourier frequency spectrum of at least two of the parameters amplitude $A(\omega)$, phase $\phi(\omega)$, amplitude of the real part $Re(\omega)$, amplitude of the imaginary part $Im(\omega)$, with ω comprising ess ntially those frequencies (f_1, f_2, ..., f_i) which were emitted fr m the transmitter antenna 2.

In an alternative embodiment the signal generator 22 may be arranged for generation of pulsed electrical signals 25 to the transmitter antenna 2 such as known in the art.

The radar shall be applied to detect the gradient of resistivity represented by the OWC situated below the approximately horizontal well. Due to sedimentologic processes, the chemical and physical parameters (mineral composition, density, resistivity, permeability) along deposited layers are more constant than across the layers. Thus the resistivity logs displayed in Fig. 4 from the vertical wells typical resistivity variations which possibly existing between the horizontal well and OWC below the well.

In a producing vertical well the OWC will due to pressure- and flow conditions be able to form an almost vertical conically shaped surface around the production well.

Water in such deep formation generally is more strongly electrically conductive, with resistivity below Ωm.

The present invention is applied in a preferred embodiment inside the oil zone of the reservoir rock. The resistivity in the oil zone may be between 150 and 1000 Ωm. The transmitter antennas and the receiver antennas for the radar waves are arranged outside on the metallic borehole string, which in a preferred embodiment is constituted by a production tubing, but which in an alternative embodiment is constituted by a lining pipe, usually made of metal. It is also possible to arrange transmitter- and receiver antennas inside the lining tube or production tube if these tubes are made of non-conductive materials, e.g. composite materials.

The tubing string 4 may comprise a production tubing or a lining or casing pipe, or corresponding. The receiver antennas 8 and the transmitter antenna 2 are situated outside of the surface of the metallic parts of the tubing string 4. If the tubing string 4 is made out of composite materials which do not comprise metal or other electrically conductive materials, the antennas 8 and 2 may be situated inside of or inside the wall of the tubing string 4.

It is also possible to fix the antennas 2 and 8 in other ways than by cementing. As an example, the borehole radar with antennas 2 and 8 may be retractable and supplied with a guiding slot/ lead fin in order to be possibly reinserted in exactly the same position and orientation in the production zone at a point of time later than the first radar detection.

Claims

1. Device for detection of electrical properties in a geological formation (9) via a well (1),
characterized by
(a) at least one transmitter antenna (2) for emission of electromagnetic waves (26), arranged by a tubing string (4), with the transmitter antenna (2) being arranged for fixed, permanent position and shielded with respect to the geological formation (9),
(b) at least one, preferably more receiver antennas (8) for the reflected electromagnetic waves (26), by preferably the same tubing string (4), the receiver antennas (8) being arranged for fixed, permanent position unshielded with respect to the geological formation (9).

2. Device according to claim 1,
characterized by
a directionally sensitive antenna group (8') comprising three or more receiver antennas (8) arranged about the tubing string's (4) axis and essentially by the same position along the tubing string (4), arranged for detecting the reflected electromagnetic waves' (26) and their reflectors' direction with respect to the tubing string's (4) axis.

3. Device according to claim 1,
characterized by
a transmitter antenna group (2') comprising two or more transmitter antennas (2) arranged about the tubing string's (4) axis and essentially by the same position along the tubing string (4), arranged for emitting electromagnetic waves mainly in a selected direction with respect to the tubing string's (4) axis.

4. Device according to claim 1, 2 or 3,
characterized by
a tubing string antenna module (4') comprising
a transmitter antenna group (2') having at least two transmitter antennas (2) arranged by a first position along

the tubing string antenna module (4'), and

at least one directionally sensitive group (8') having at least three receiver antennas (8) arranged by a second position along the tubing string antenna module (4').

5. Device according to claim 4,
c h a r a c t e r i z e d i n t h a t the tubing string antenna module (4') comprises

a transmitter antenna group (2') having preferably two dipole transmitter antennas (2) arranged on either side of the tubing string antenna module (4') by a first position along the tubing string antenna module (4'),

a first directionally sensitive group (8') having preferably four dipole receiver antennas (8) arranged with even angular separation about the tubing string antenna module (4') by a second position along the tubing string antenna module (4'),

a second directionally sensitive group (8') having preferably four dipole receiver antennas (8) arranged with even angular separation about the tubing string antenna module (4') by a third position along the tubing string antenna module (4'), preferably at the opposite side of the transmitter antenna group (2') with respect to the first directionally sensitive group (8').

6. Device according to one of the previous claims,
c h a r a c t e r i z e d b y
an electronics package (20) comprising:

a signal generator (22) for generation of electromagnetic signals (25) to the transmitter antenna (2),

devices (80) for reception of signals ($85_1, 85_2, .., 85_n$) induced in each of the receiver antennas ($8_1, 8_2, .., 8_n$),

signal processing means (82) for processing of the received signals ($85_1, 85_2, .., 85_n$),

communication devices (100) for transmission of signals (105) representing the electrical signals ($85_1, 85_2, .., 85_n$), and for reception of control signals (205).

7. Device according to one of the claim 1-6,
c h a r a c t e r i z e d i n t h a t

the signal generator (22) for generation of electrical signals (25) to the transmitter antenna (2) is arranged for generation of coherent continuous electromagnetic waves (26) from the transmitter antenna (2).

8. Device according to claim 7,
c h a r a c t e r i z e d i n t h a t
the signal generator (22) is arranged for generation of electrical signals (25) to the transmitter antenna for emission of coherent continuous waves at a number of i different frequencies f_1, f_2, ..., f_i from the transmitter antenna (2).

9. Device according to one of the previous claims,
c h a r a c t e r i z e d b y
an impedance adjustment device (23) arranged for adjusting the transmitter antenna's (2) impedance to each particular of the emitted discrete frequencies f_1, f_2, ..., f_i , for maximal effect emission to the geological formation (9).

10. Device according to one of the previous claims,
c h a r a c t e r i z e d i n
an impedance adjustment device (83) arranged to adjust the receiver antennas (8) impedance to each particular of the emitted discrete frequencies f_1, f_2, ..., f_i .

11. Device according to claim 1,
c h a r a c t e r i z e d b y
cancelling devices (28) arranged for cancelling of direct waves or directly coupled signals between the transmitter antenna (2) and the receiver antenna (8).

12. Device according to claim 11,
c h a r a c t e r i z e d b y
differential coupling between receiver antennas (8), optionally differential coupling between the transmitter antenna (2) and the receiver antenna (8).

13. Device according to claim 6,
c h a r a c t e r i z e d i n t h a t

the electronics package (20) is situated in the immediate vicinity of the antennas (2, 8).

14. Device according to claim 5 and 13,
characterized in that
the tubing string antenna module (4') comprises the electronics package (20).

15. Device according to claim 13 or 14,
characterized in that
the electronics package (20) additionally comprises an address unit (55), an accumulating- and charging unit (56), a memory (54) and a rest mode unit (57).

16. Device according to one of the previous claims,
characterized by
a preferably electrical energy supply- and communication line (7) arranged between the communication unit (100) in the electronics package (20) and the control unit (200).

17. Device according to one of the previous claims,
characterized in that
the control unit (200) is situated at the sea bottom or the surface of the earth.

18. Device according to one of the previous claims,
characterized in that
the signal processing means (82) for processing of the received signals ($85_1, 85_2, \ldots, 85_n$), is arranged to form at least one discrete Fourier frequency spectrum of at least two of the parameters amplitude $A(\omega)$, phase $\phi(\omega)$, amplitude of the real part $Re(\omega)$, amplitude of the imaginary part $Im(\omega)$, with ω comprising essentially those frequencies (f_1, f_2, ..., f_i) which were emitted from the transmitter antenna (2).

19. Device according to claim 6,
characterized in that
the signal generator (22) generates pulsed electrical signals (25) to the transmitter antenna (2).

20. Device according to claim 11 and 17,
c h a r a c t e r i z e d i n
cancelling of direct waves or directly coupled signals between the transmitter antenna (2) by means of delayed sampling at the receiver antenna (8).

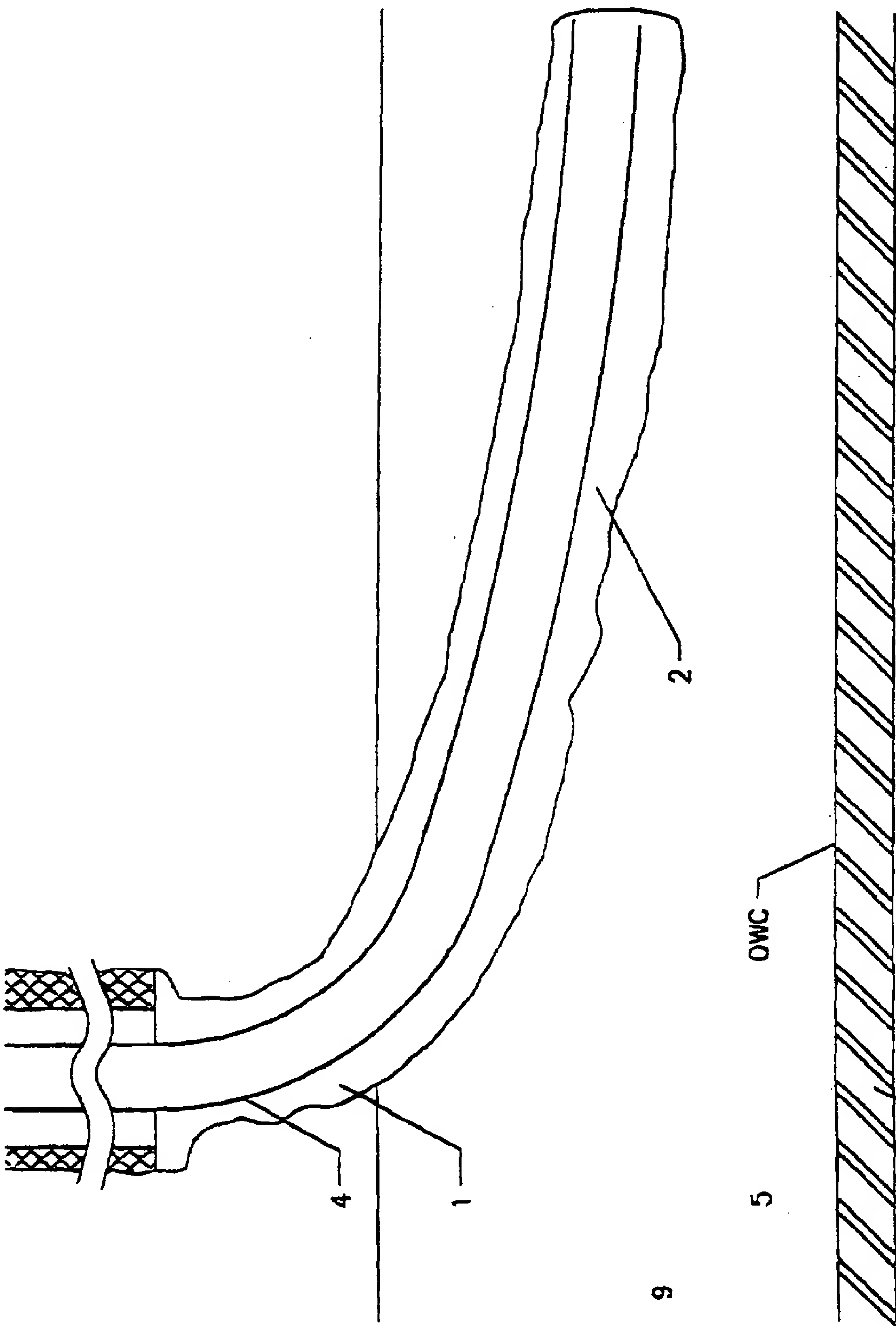


FIG. 1

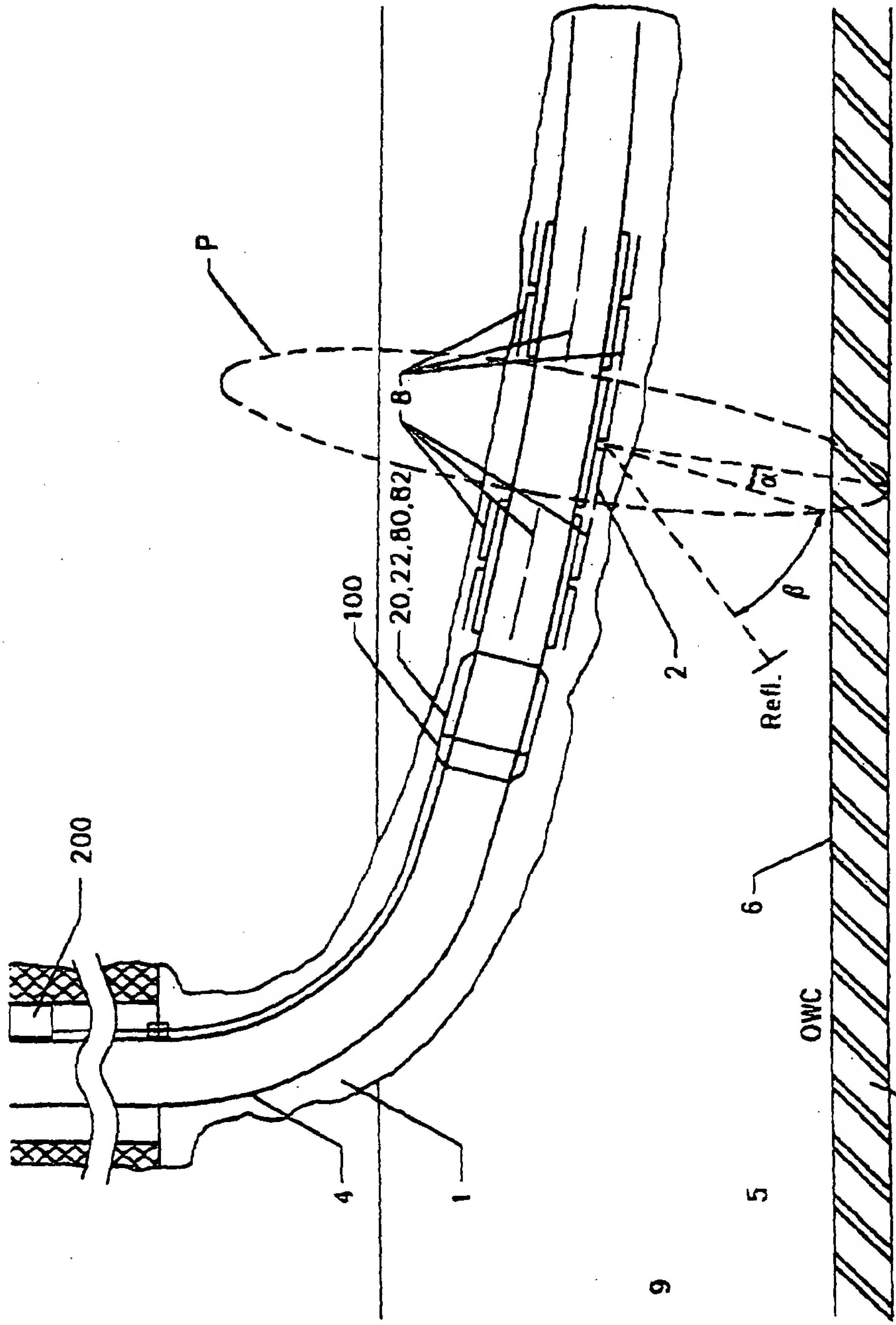
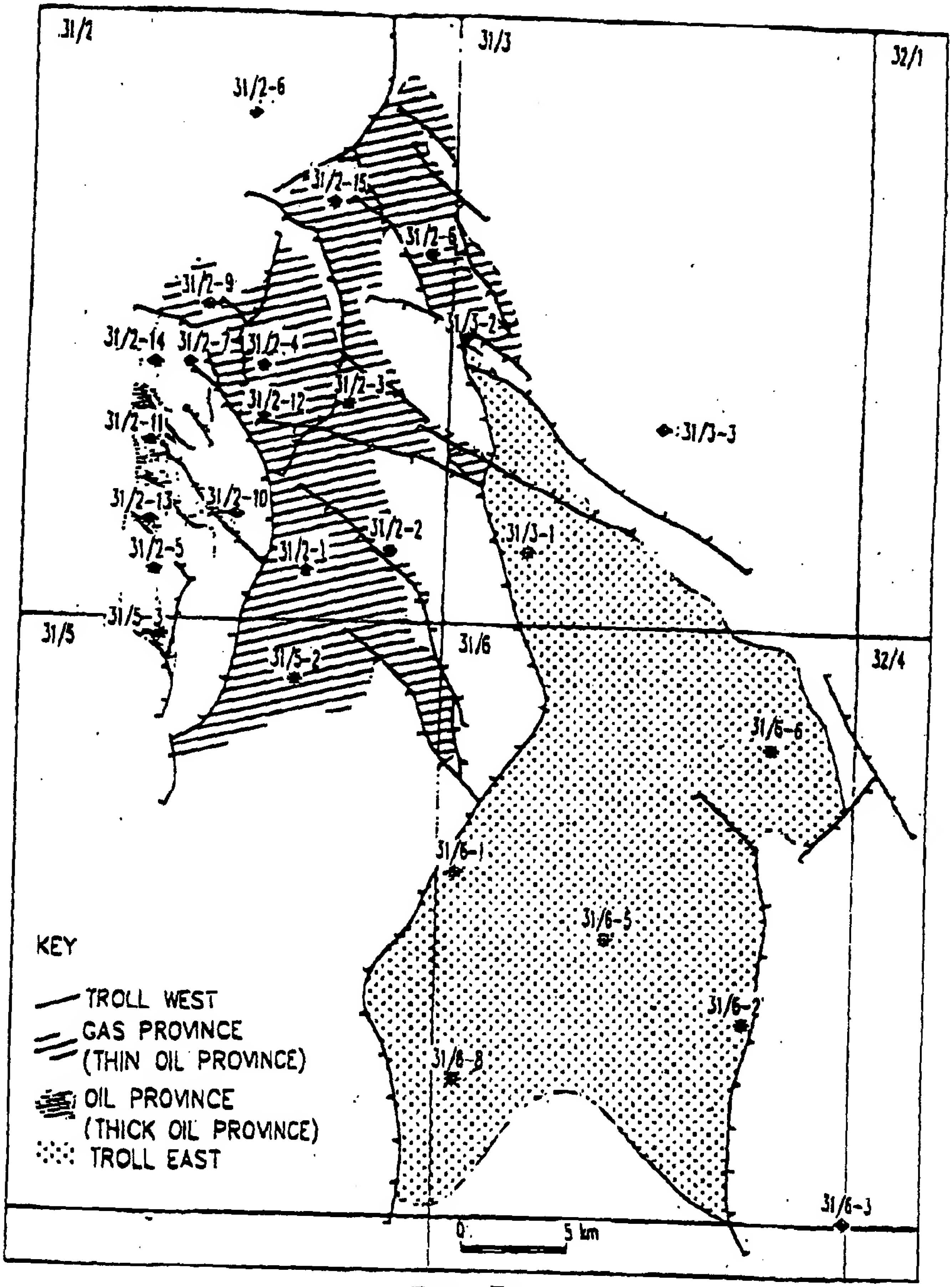


FIG. 2


31/2
31/3
32/1
31/2-6
31/2-15
31/2-8
31/2-9
31/2-14
31/2-7
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31/3-2
31/2-3
31/2-12
31/2-11
31/3-3
31/2-13
31/2-10
31/2-2
31/3-1
31/2-5
31/2-1
31/5-3
31/5
31/6
31/5-2
32/4
31/6-6
31/6-1
31/6-5
31/6-2
31/6-8
31/6-3
0
5 km
KEY
TROLL WEST
GAS PROVINCE
(THIN OIL PROVINCE)
OIL PROVINCE
(THICK OIL PROVINCE)
TROLL EAST

FIG. 3a

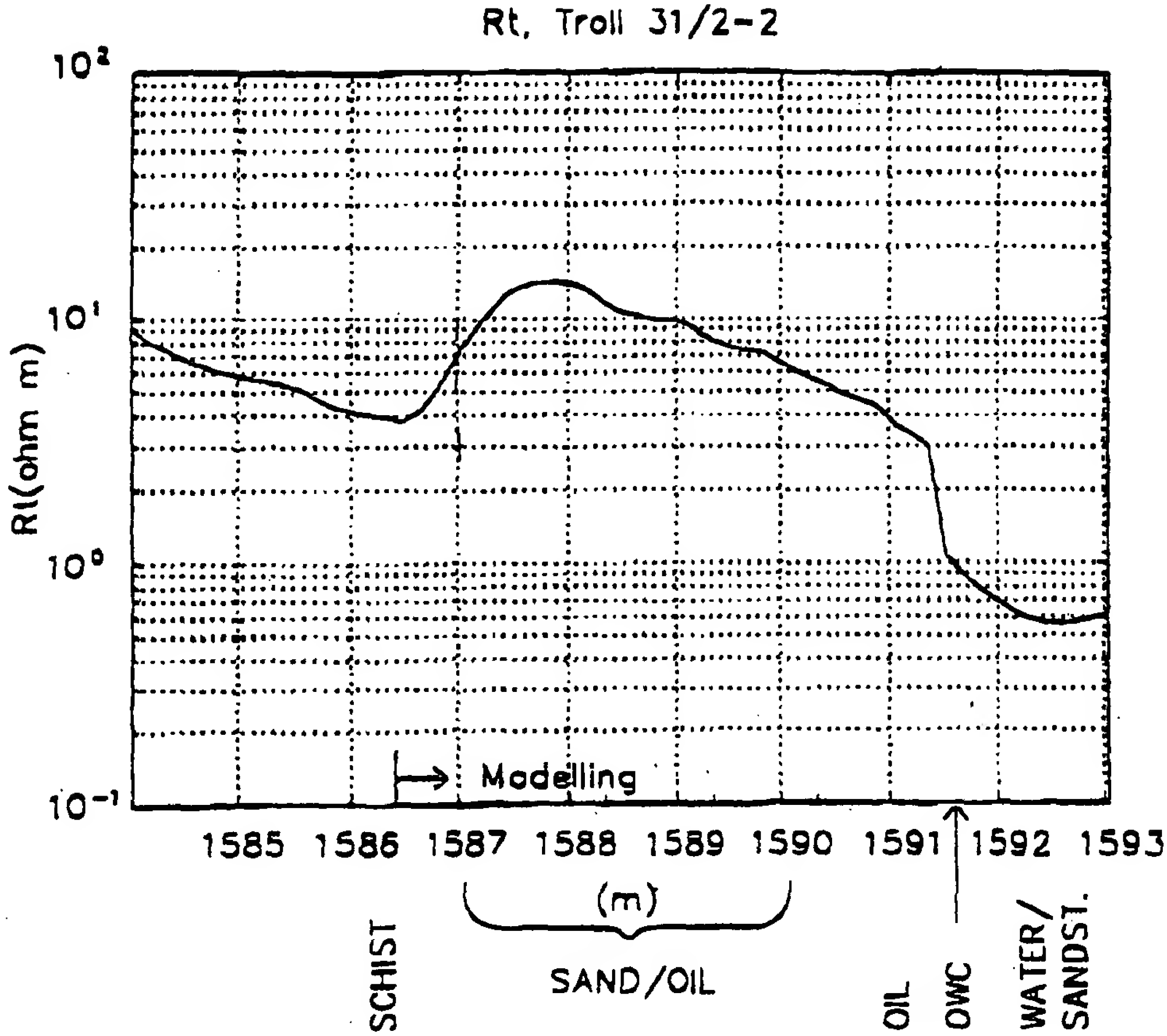
Rt, Troll 31/2-2
Rl(ohm m)
10^2
10^1
10^0
10^{-1}
Modelling
1585 1586 1587 1588 1589 1590 1591 1592 1593
(m)
SCHIST
SAND/OIL
OIL
OWC
WATER/ SANDST.

FIG. 3b

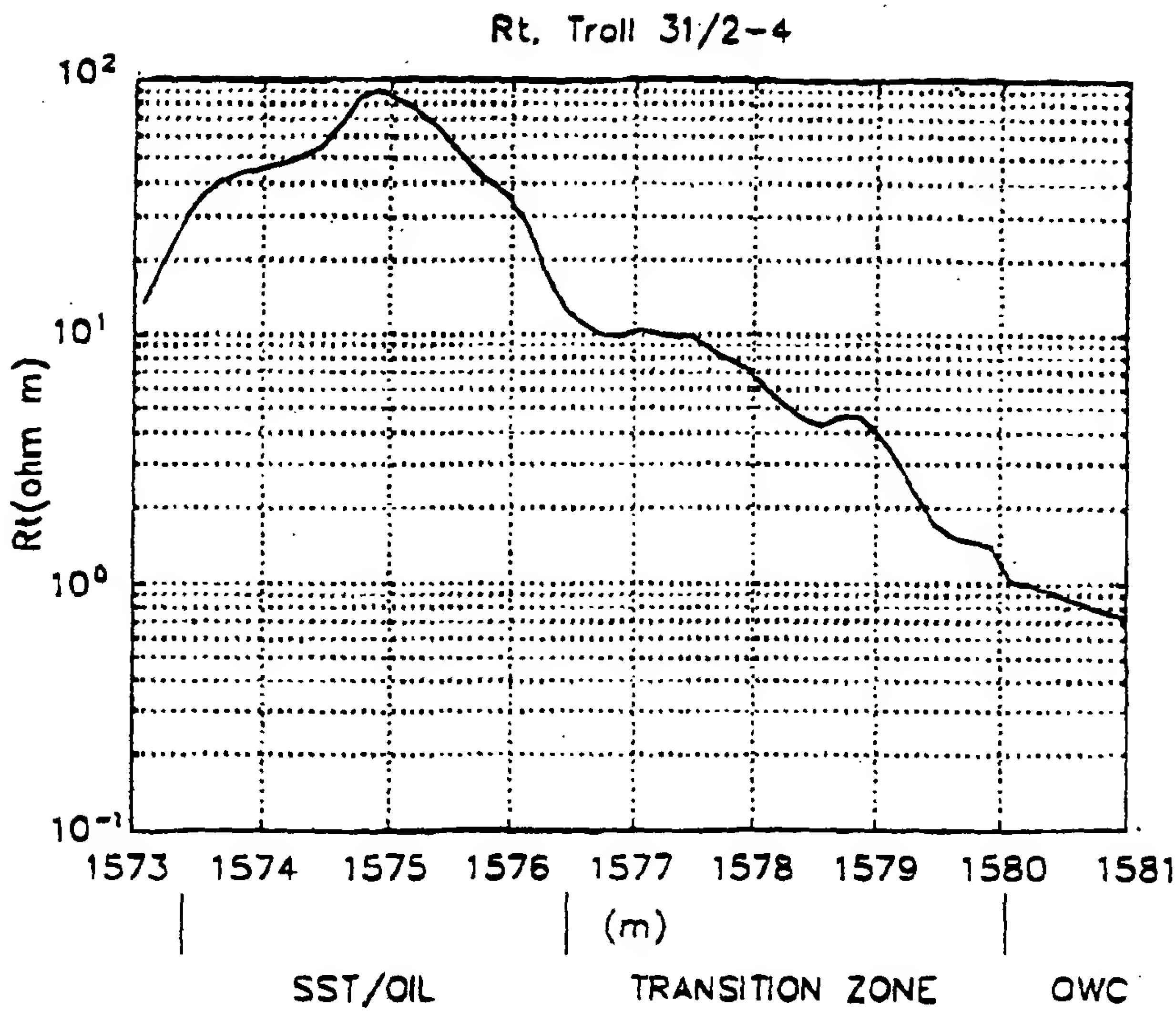
Rt. Troll 31/2-4
Rt(ohm m)
10²
10¹
10⁰
10⁻¹
1573
1574
1575
1576
1577
1578
1579
1580
1581
(m)
SST/OIL
TRANSITION ZONE
OWC

FIG. 3c

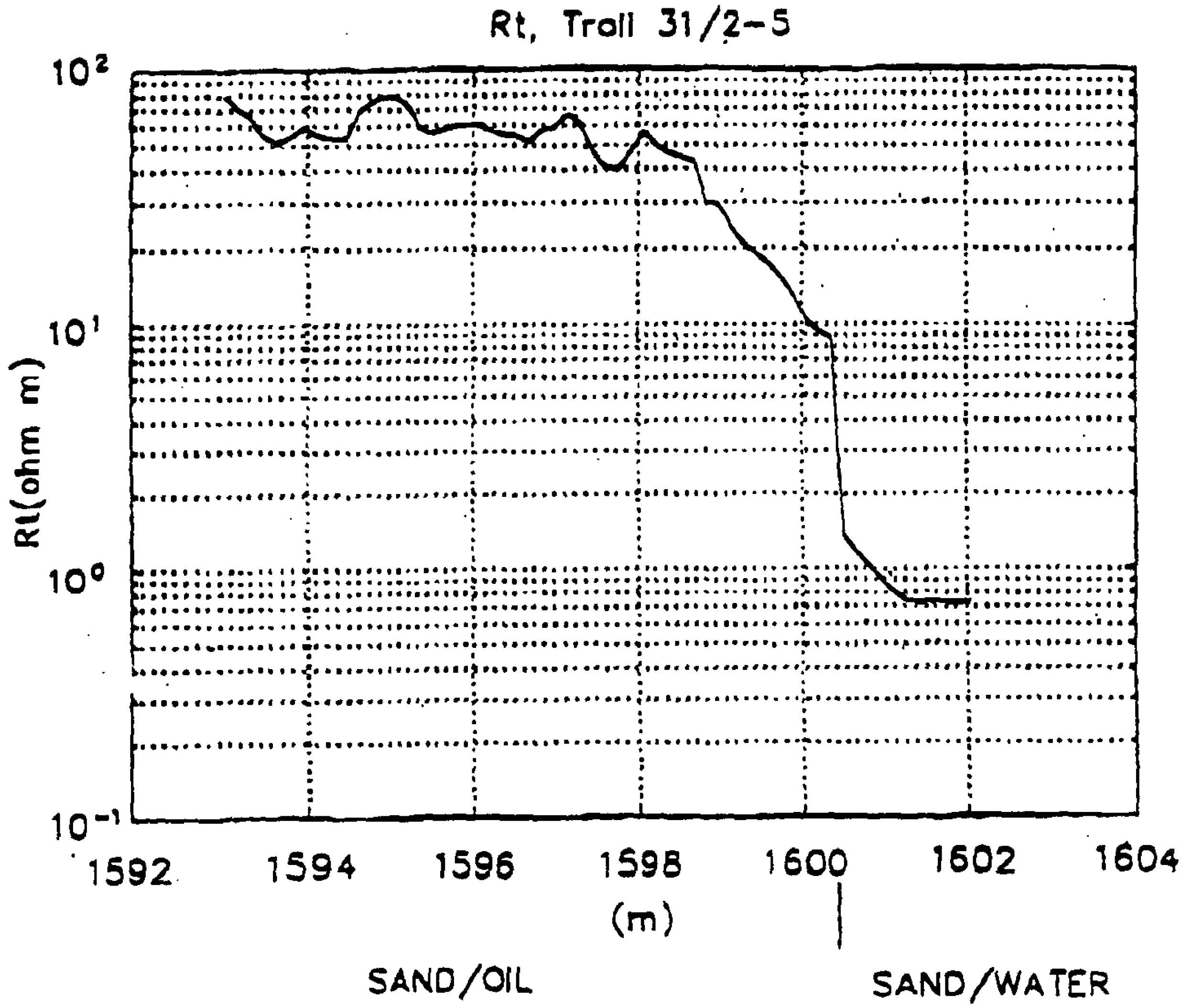
Rt, Troll 31/2-5
10^2
10^1
10^0
10^{-1}
Rt(ohm m)
1592
1594
1596
1598
1600
1602
1604
(m)
SAND/OIL
SAND/WATER

FIG. 3d

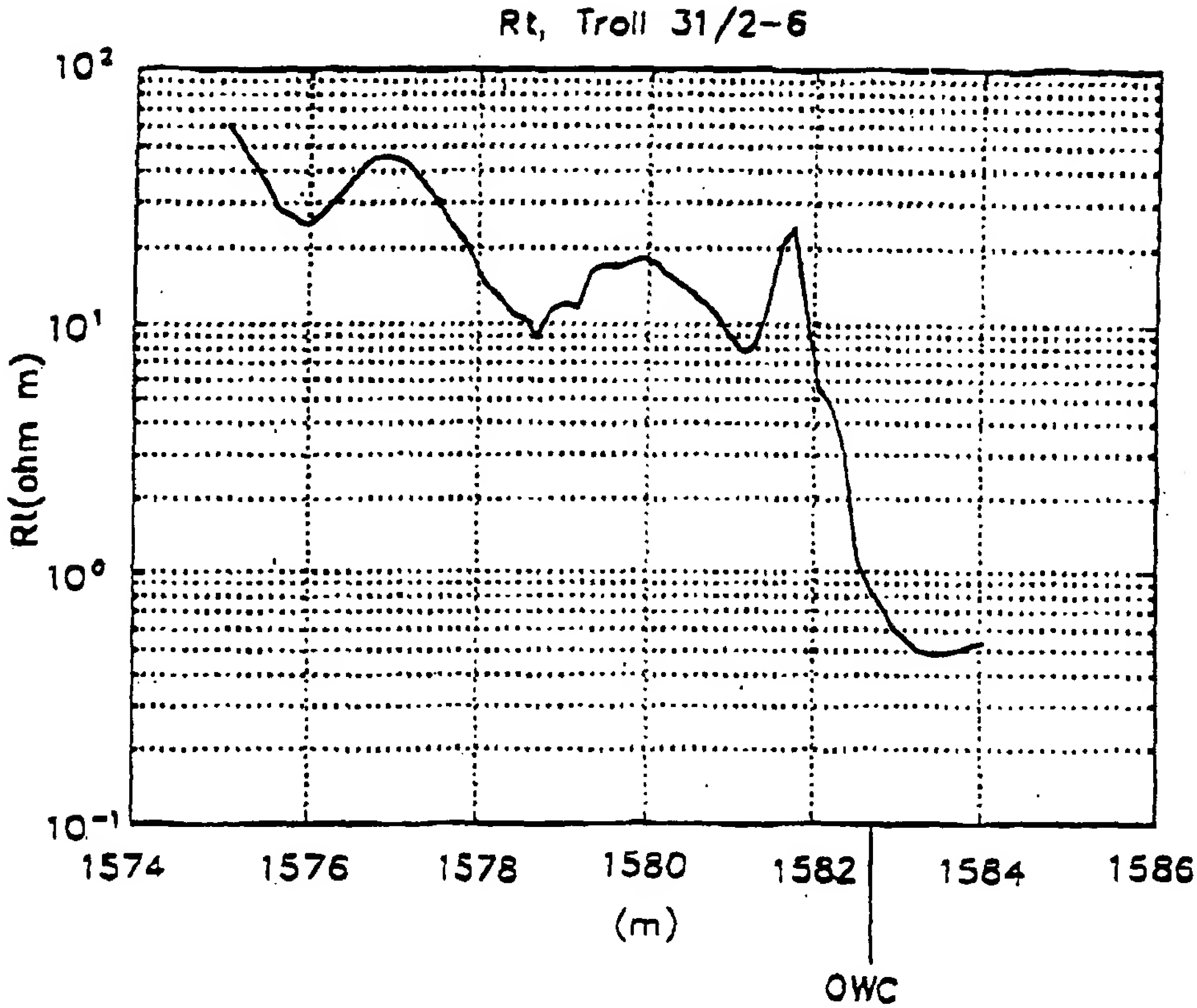
Rt, Troll 31/2-6
10^2
10^1
10^0
10^{-1}
Rt(ohm m)
1574
1576
1578
1580
1582
1584
1586
(m)
OWC

FIG. 3e

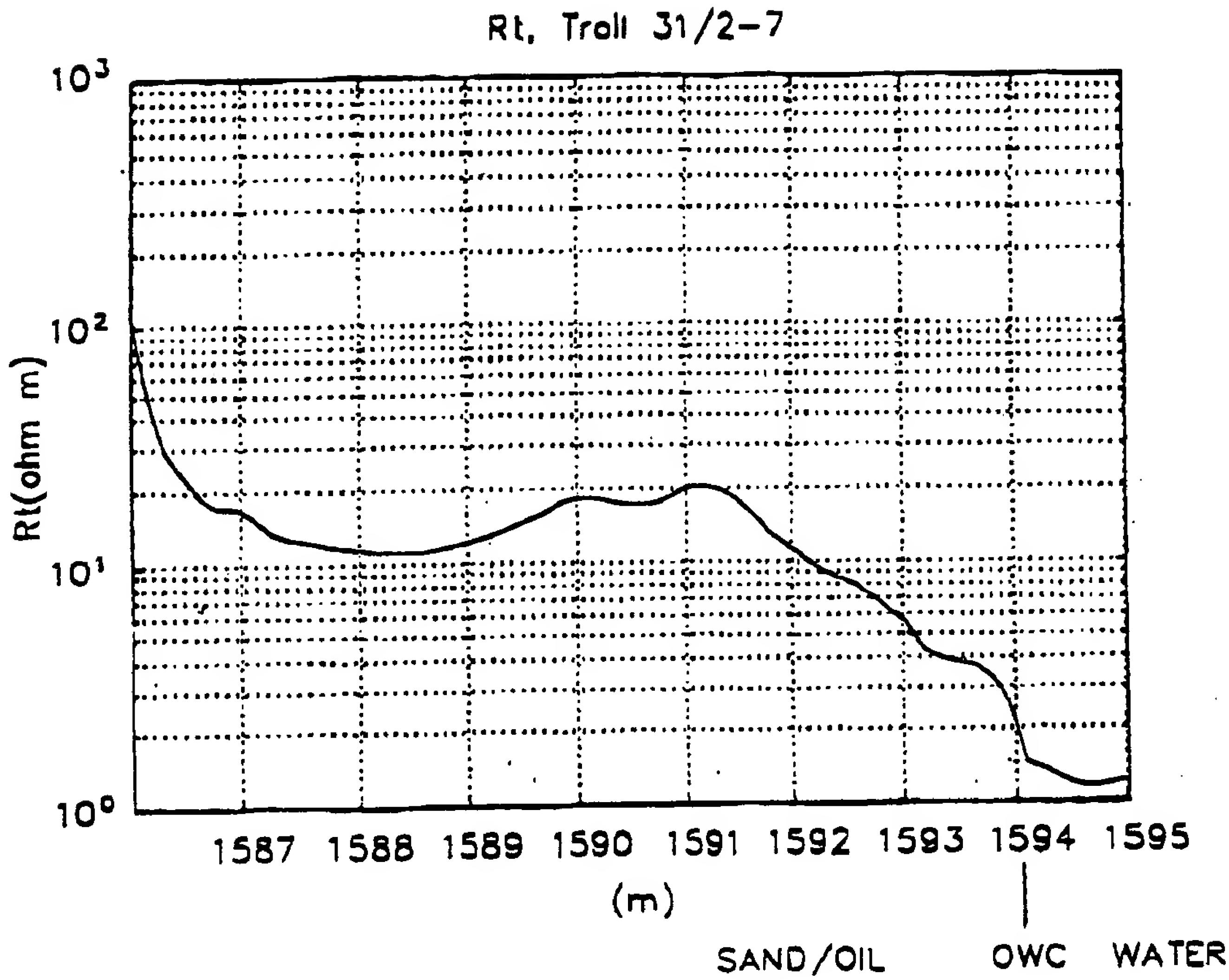
Rt, Troll 31/2-7
10^3
10^2
10^1
10^0
Rt(ohm m)
1587 1588 1589 1590 1591 1592 1593 1594 1595
(m)
SAND/OIL
OWC
WATER

FIG. 3f

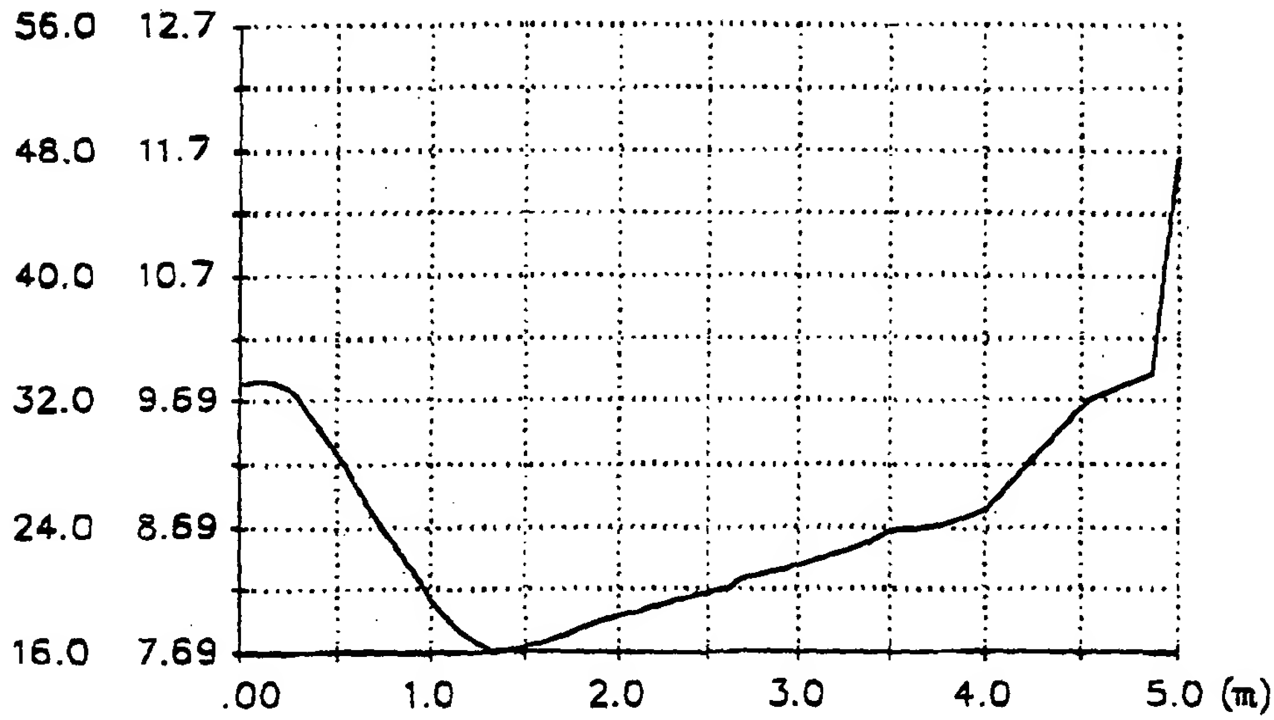

FIG. 4a

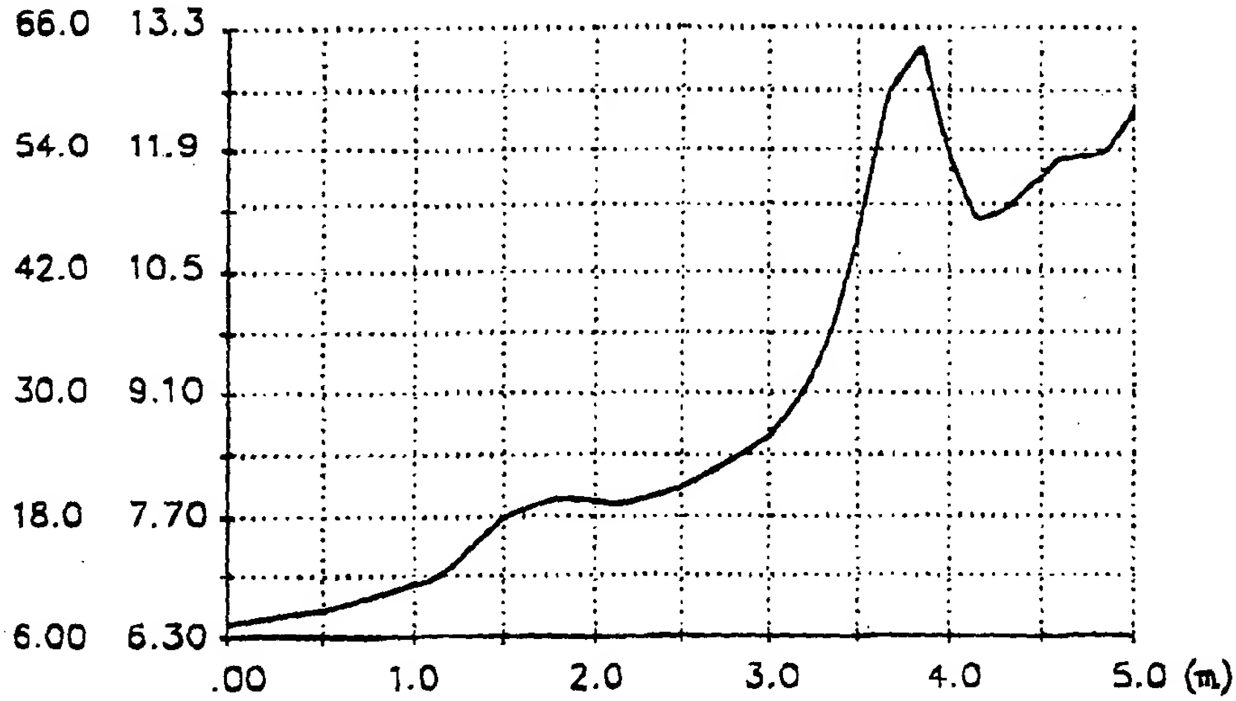

FIG. 4b

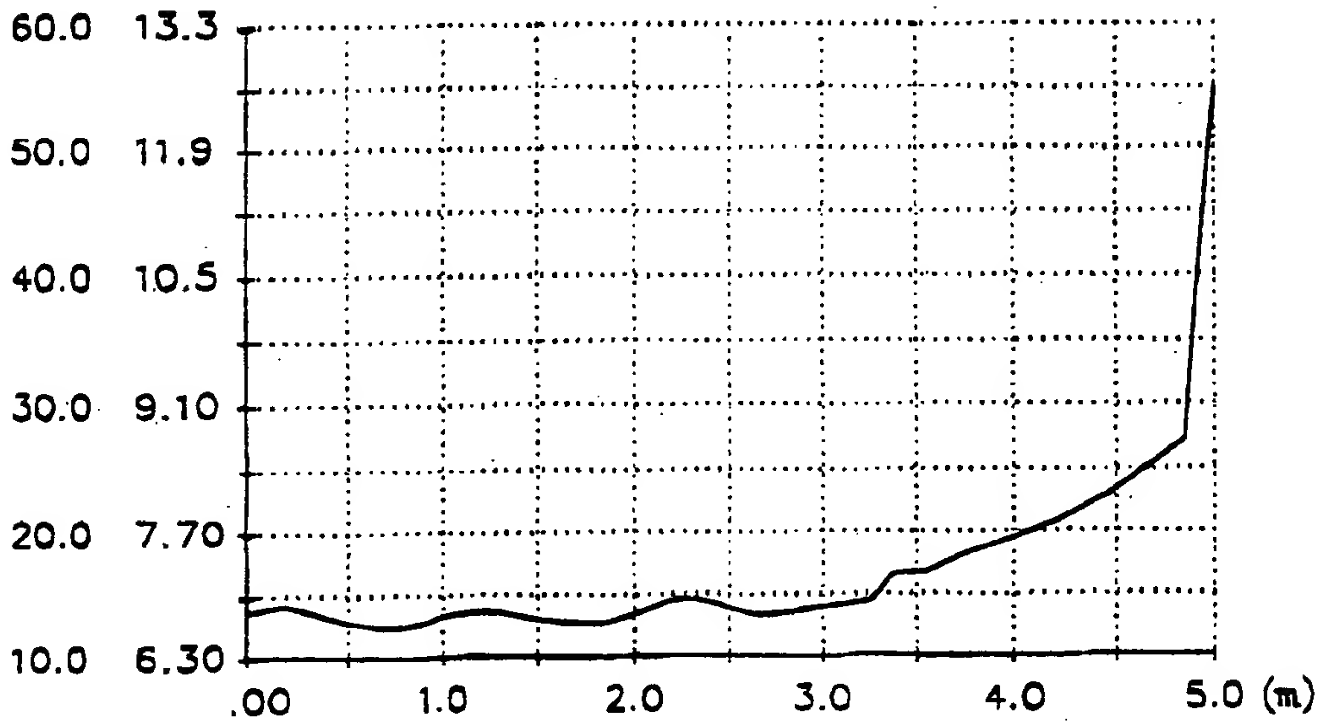

FIG. 4c

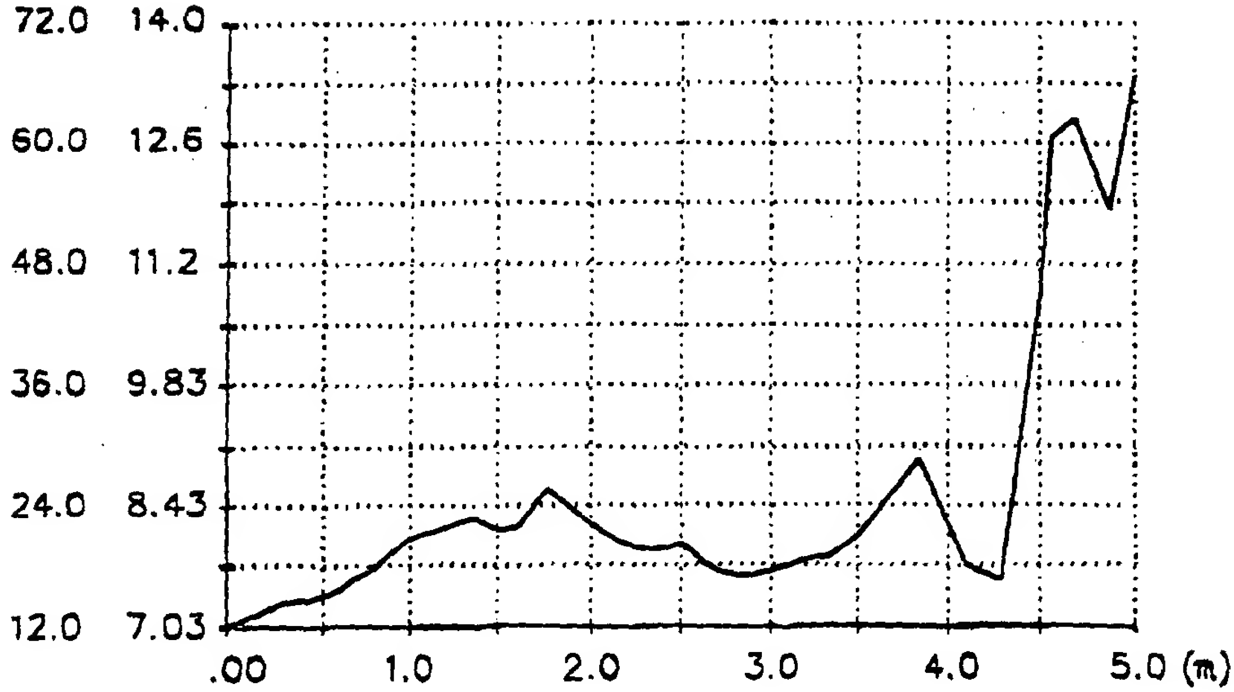

FIG. 4d

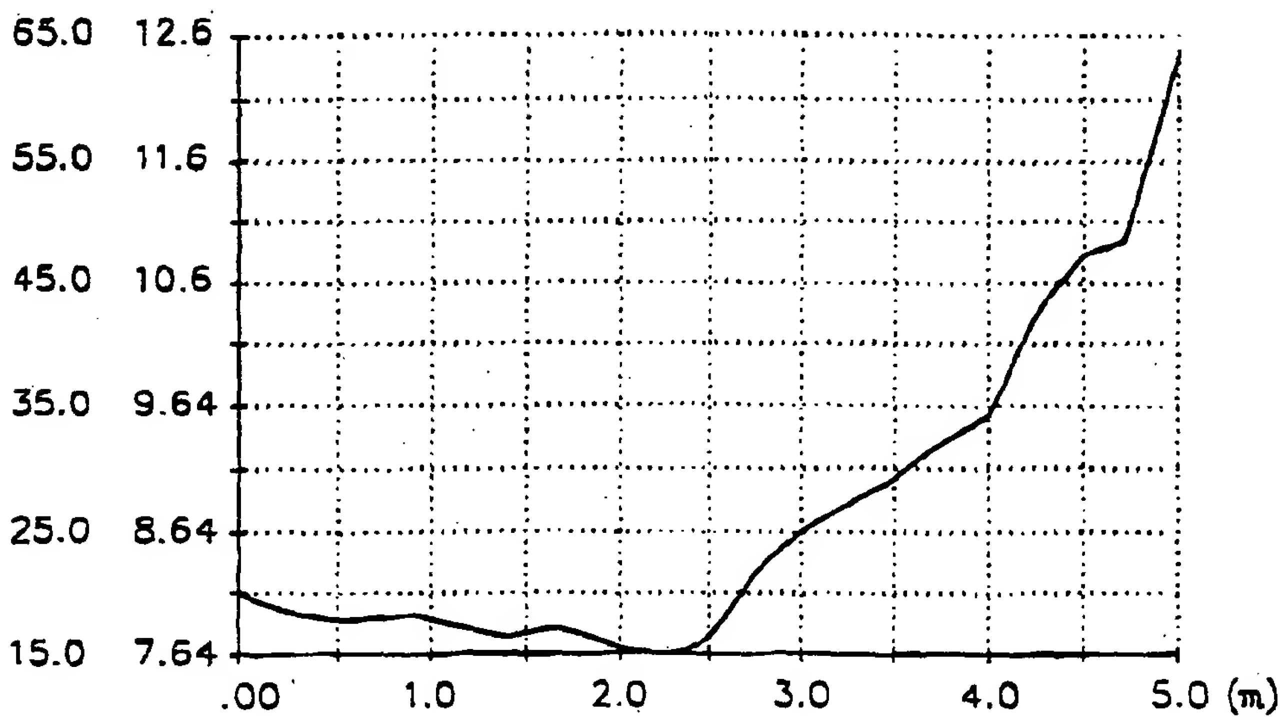

FIG. 4e

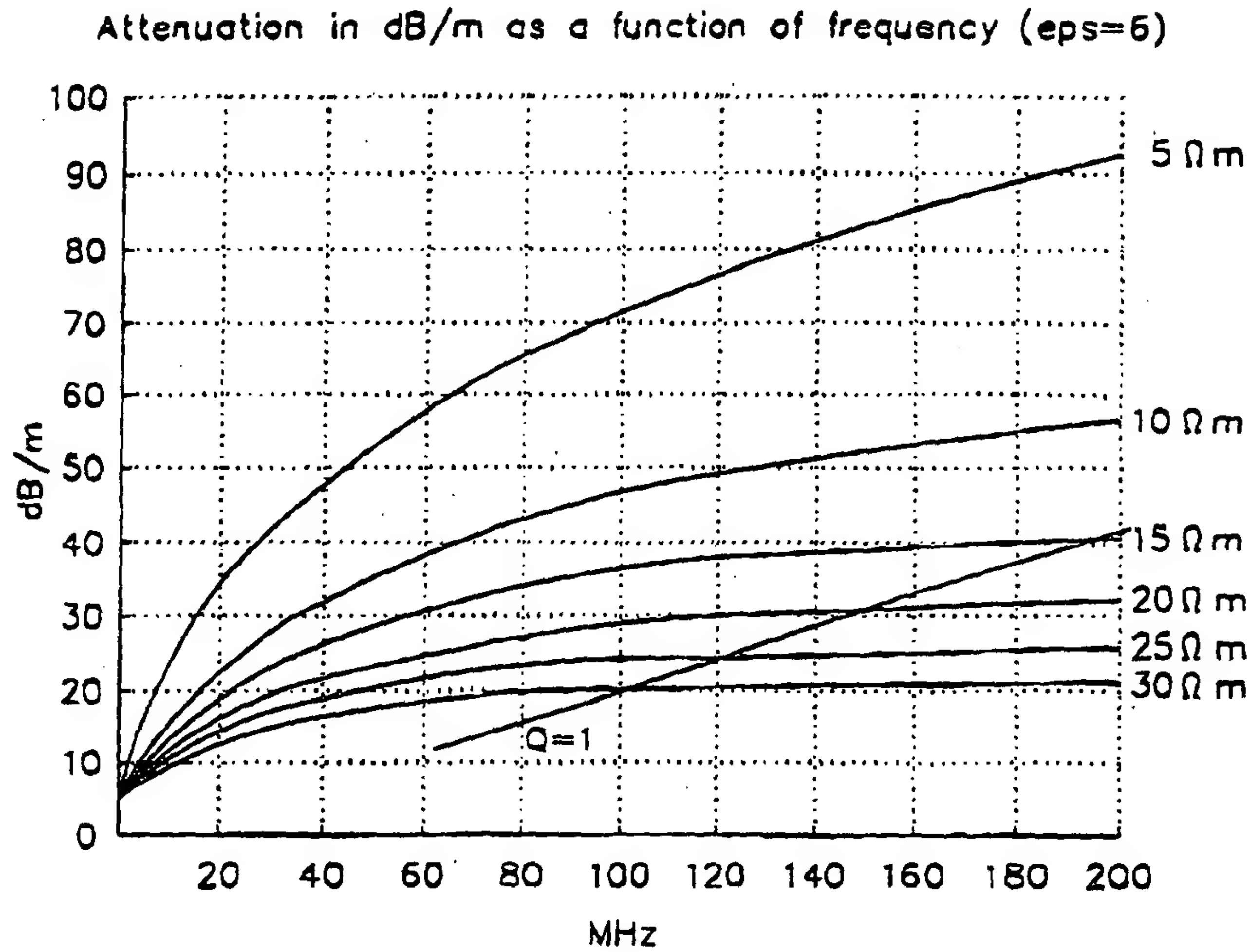
Attenuation in dB/m as a function of frequency (eps=6)
dB/m
100
90
80
70
60
50
40
30
20
10
0
20
40
60
80
100
120
140
160
180
200
MHz
5 Ω m
10 Ω m
15 Ω m
20 Ω m
25 Ω m
30 Ω m
Q=1

FIG. 5a

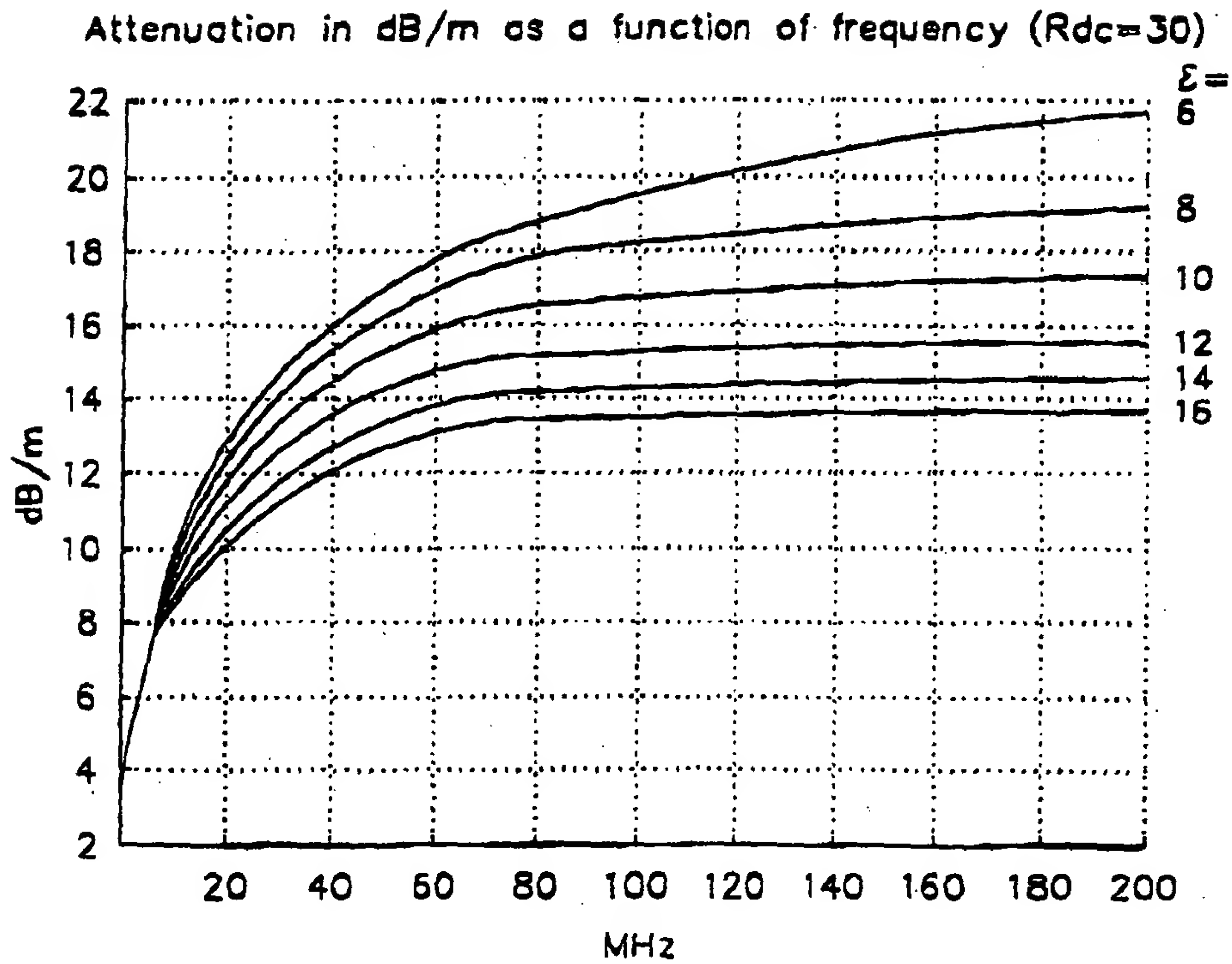
Attenuation in dB/m as a function of frequency (Rdc=30)
ε=
6
8
10
12
14
16
22
20
18
16
14
12
10
8
6
4
2
dB/m
20
40
60
80
100
120
140
160
180
200
MHz

FIG. 5b

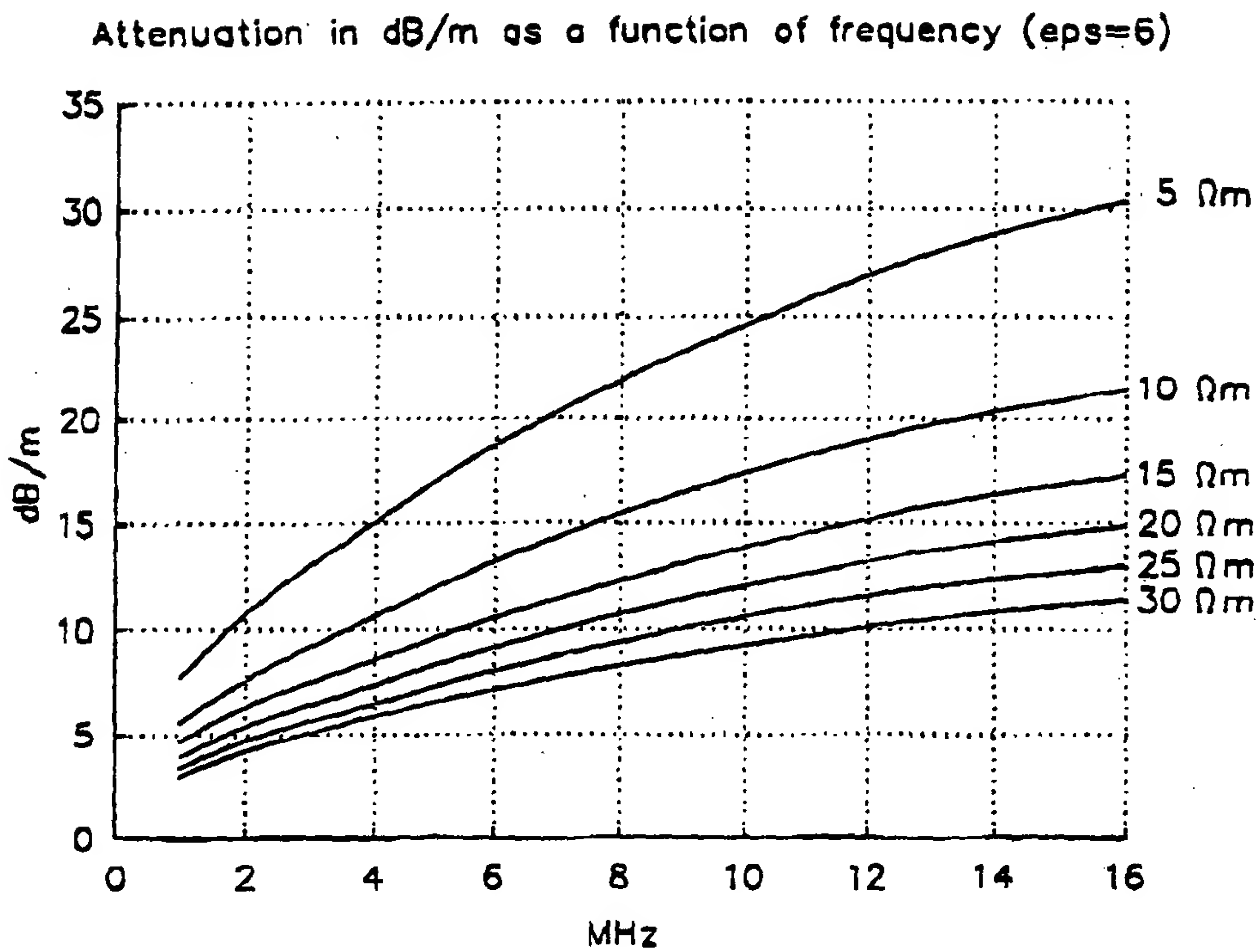
Attenuation in dB/m as a function of frequency (eps=6)
35
30
25
20
15
10
5
0
dB/m
0
2
4
6
8
10
12
14
16
MHz
5 Ωm
10 Ωm
15 Ωm
20 Ωm
25 Ωm
30 Ωm

FIG. 5c

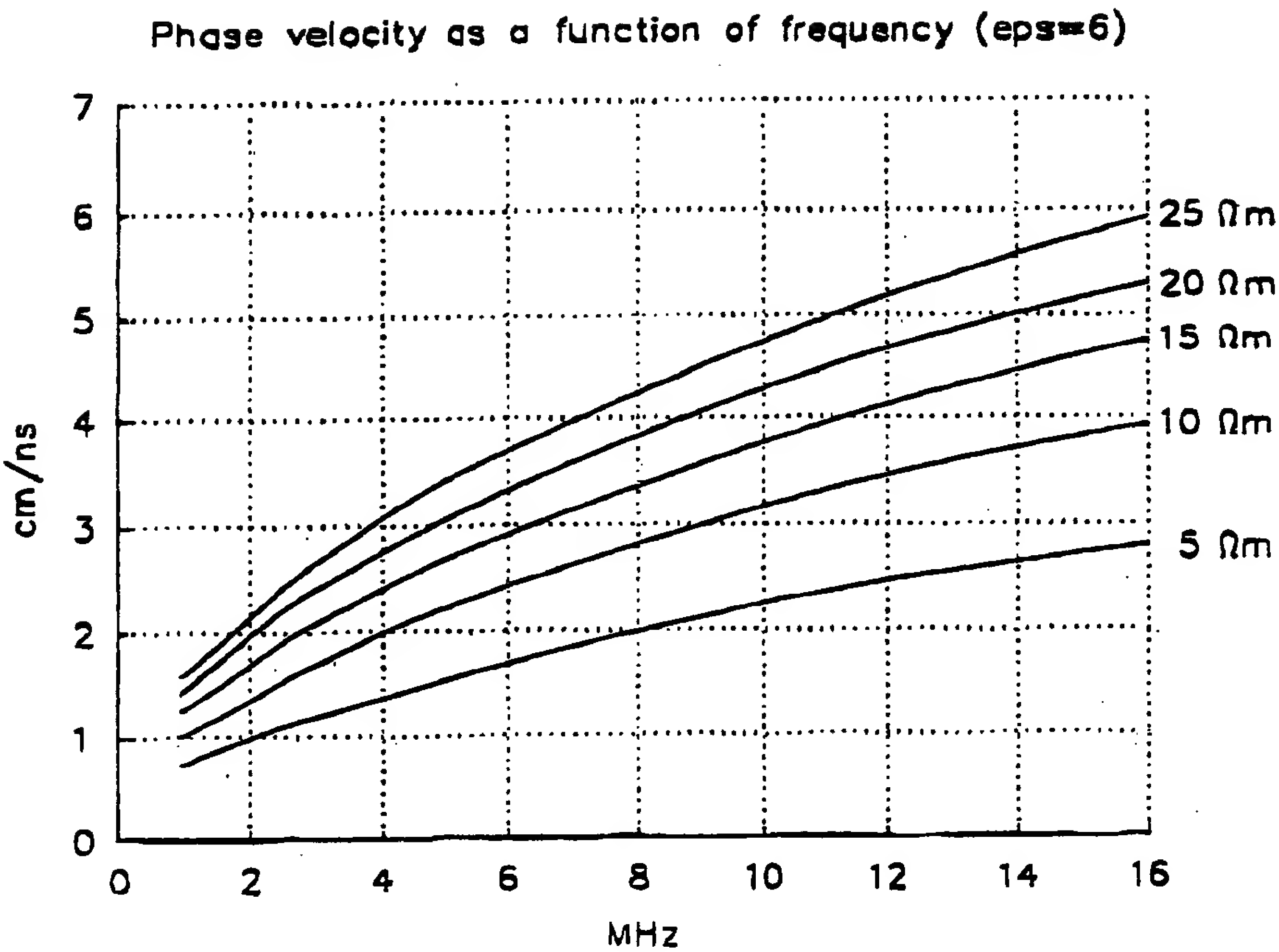
Phase velocity as a function of frequency (eps=6)
cm/ns
0
1
2
3
4
5
6
7
0
2
4
6
8
10
12
14
16
MHz
25 Ωm
20 Ωm
15 Ωm
10 Ωm
5 Ωm

FIG. 5d

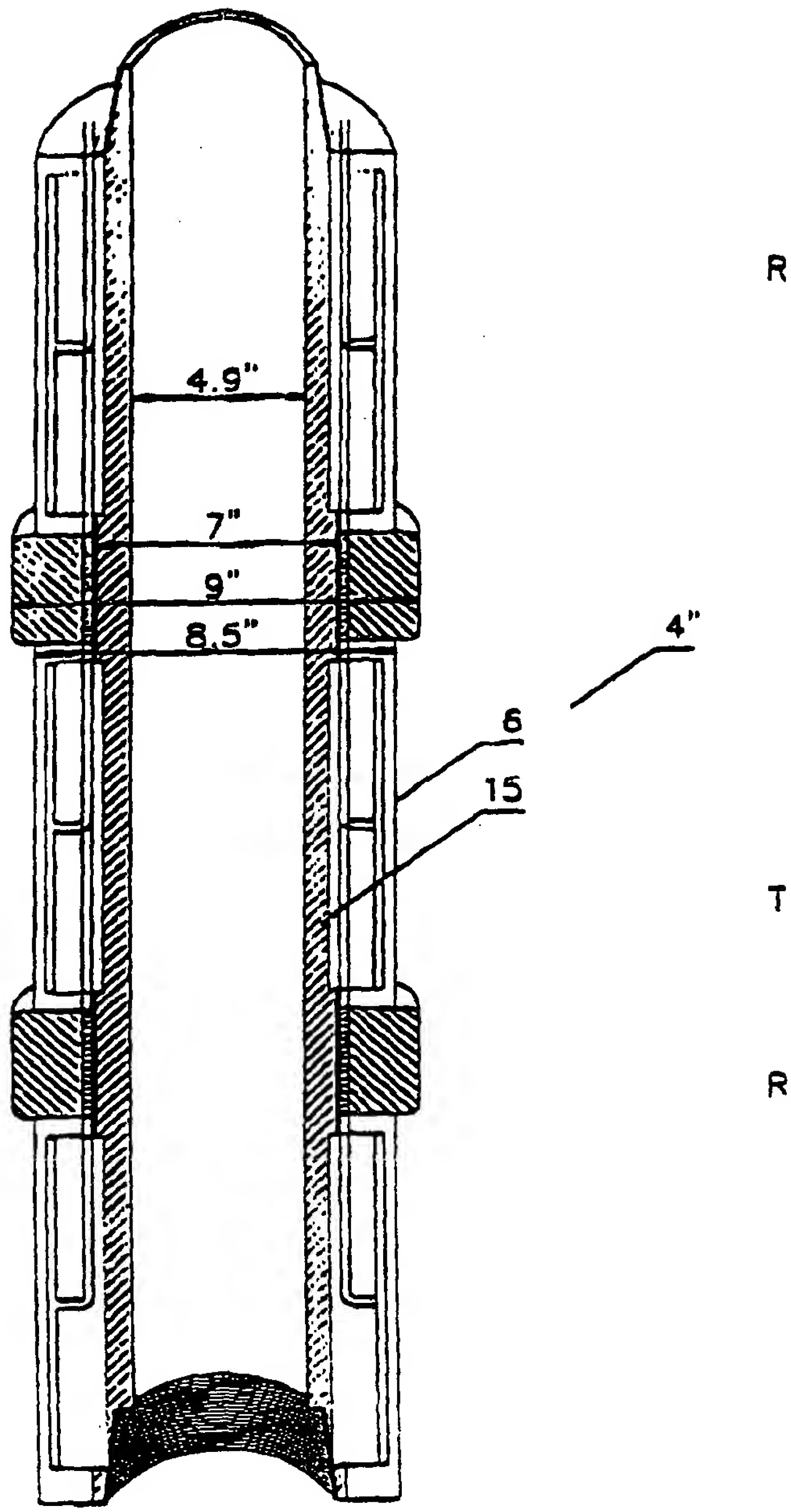

Fig. 6a

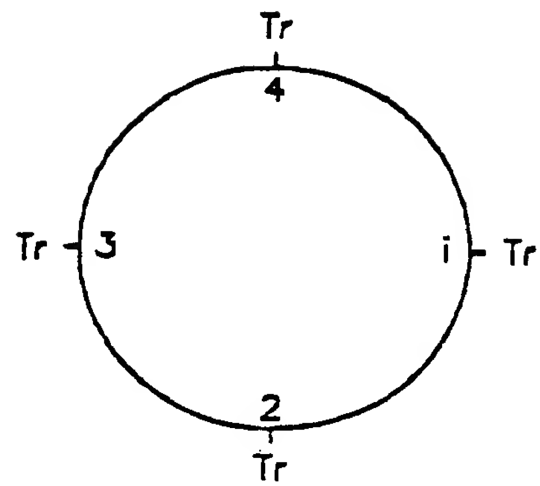

Fig. 6a (cont.)

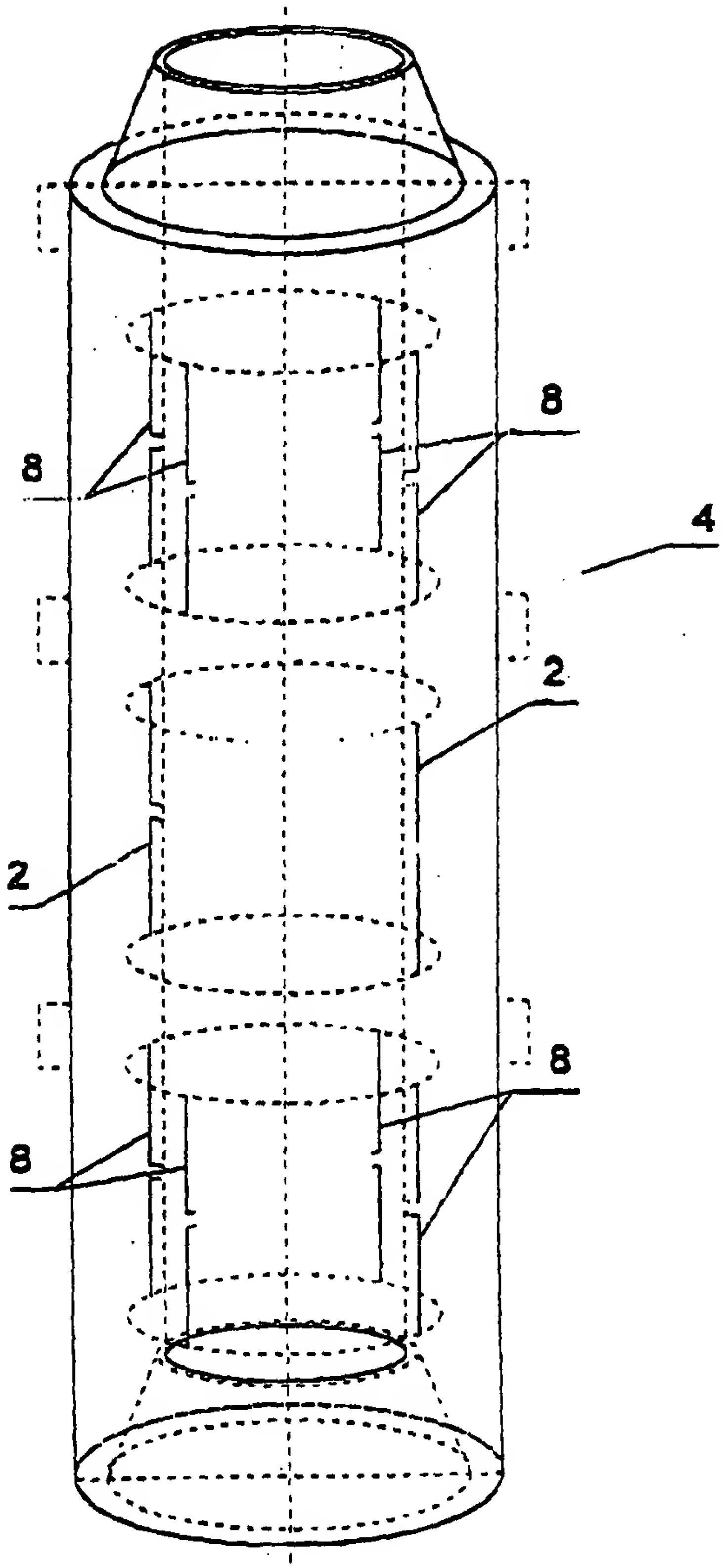

Fig. 6b

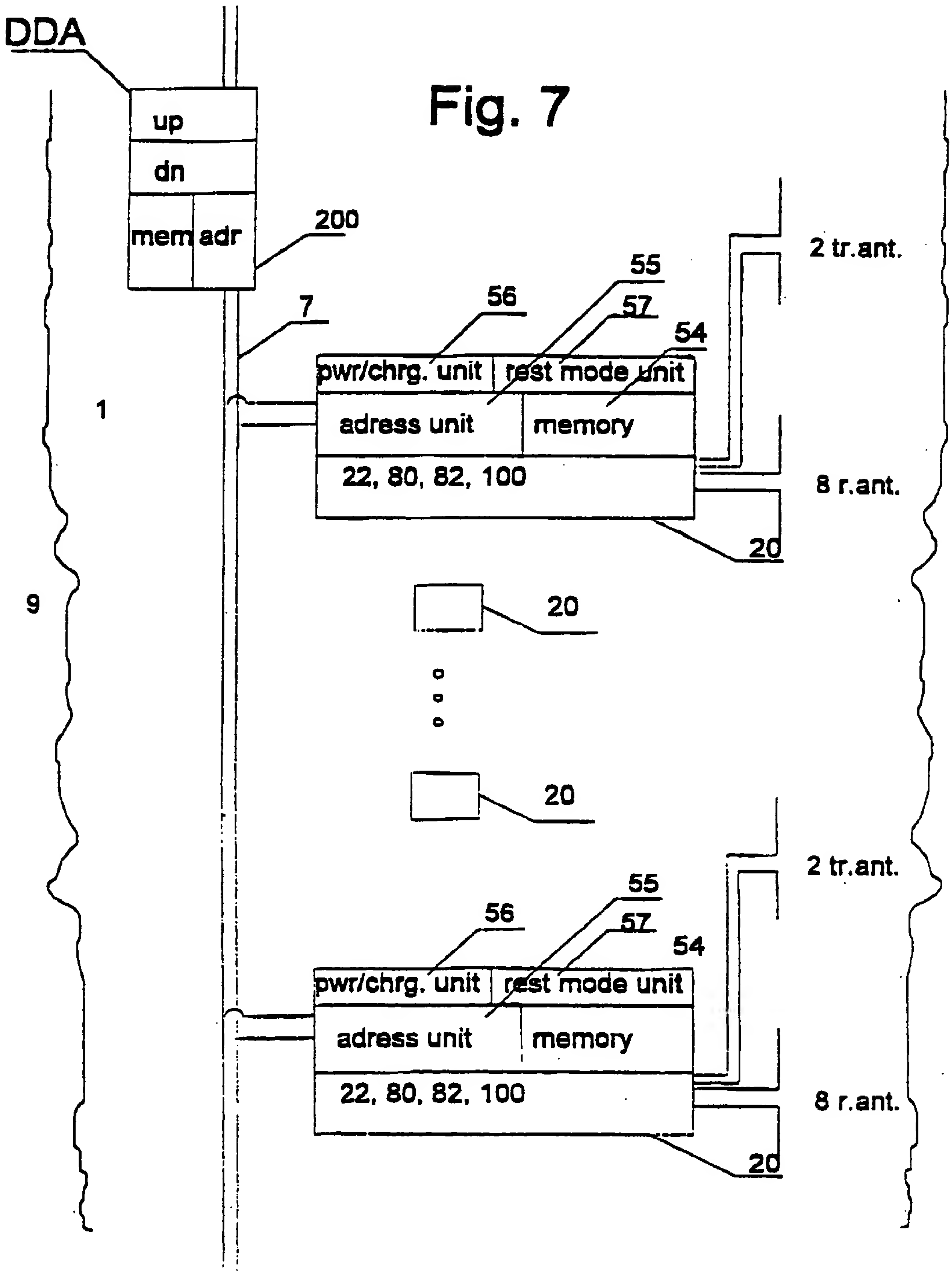
DDA
up
dn
mem
adr
200
7
56
55
57
54
pwr/chrg. unit
rest mode unit
adress unit
memory
22, 80, 82, 100
2 tr.ant.
8 r.ant.
20
1
9
20
20
56
55
57
54
pwr/chrg. unit
rest mode unit
adress unit
memory
22, 80, 82, 100
2 tr.ant.
8 r.ant.
20

Fig. 7

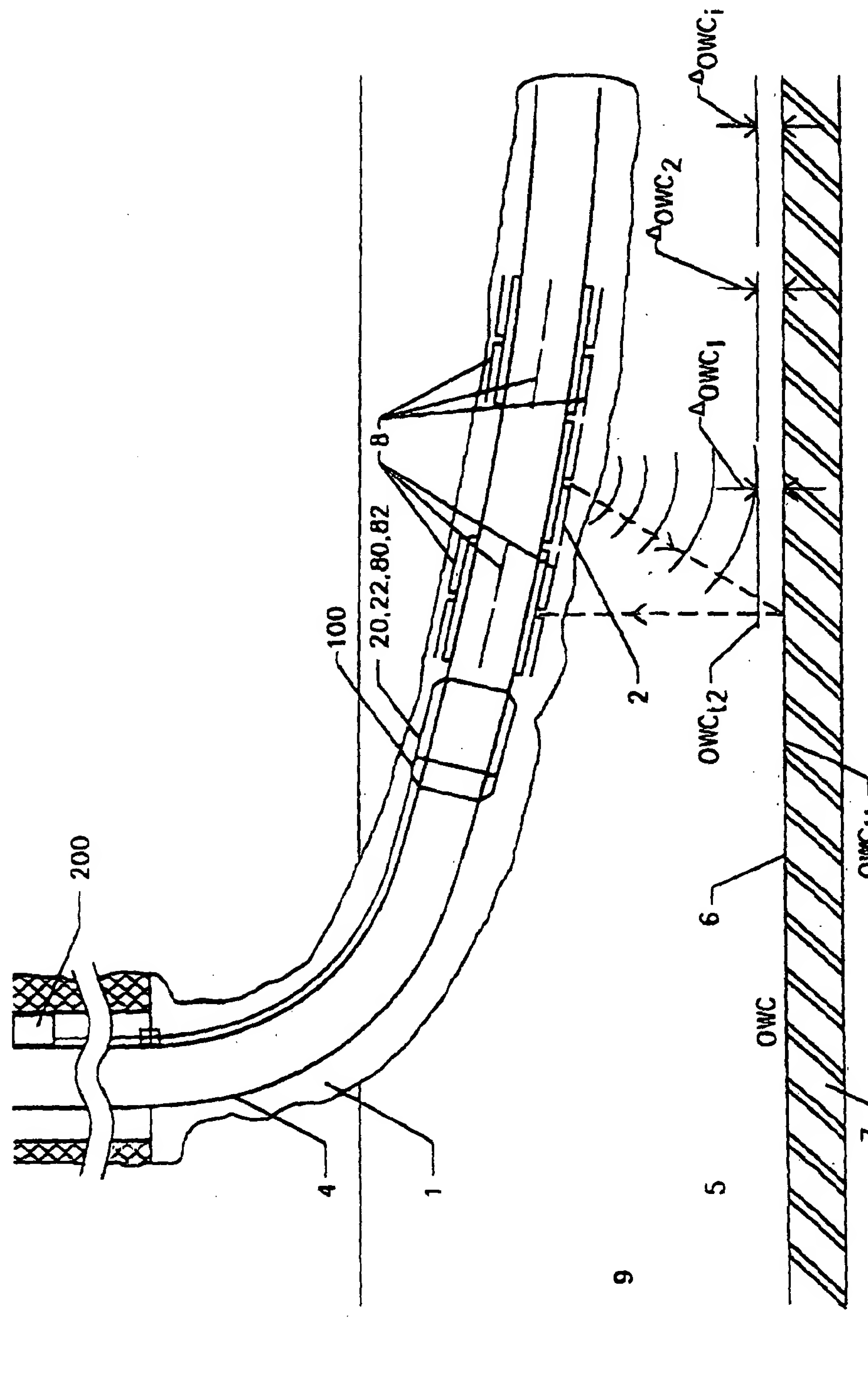
200
100
20,22,80,82
8
8
2
4
1
5
6
7
9
OWC
OWC$_{t1}$
OWC$_{t2}$
Δ_{OWC_1}
Δ_{OWC_2}
Δ_{OWC_i}

FIG. 8

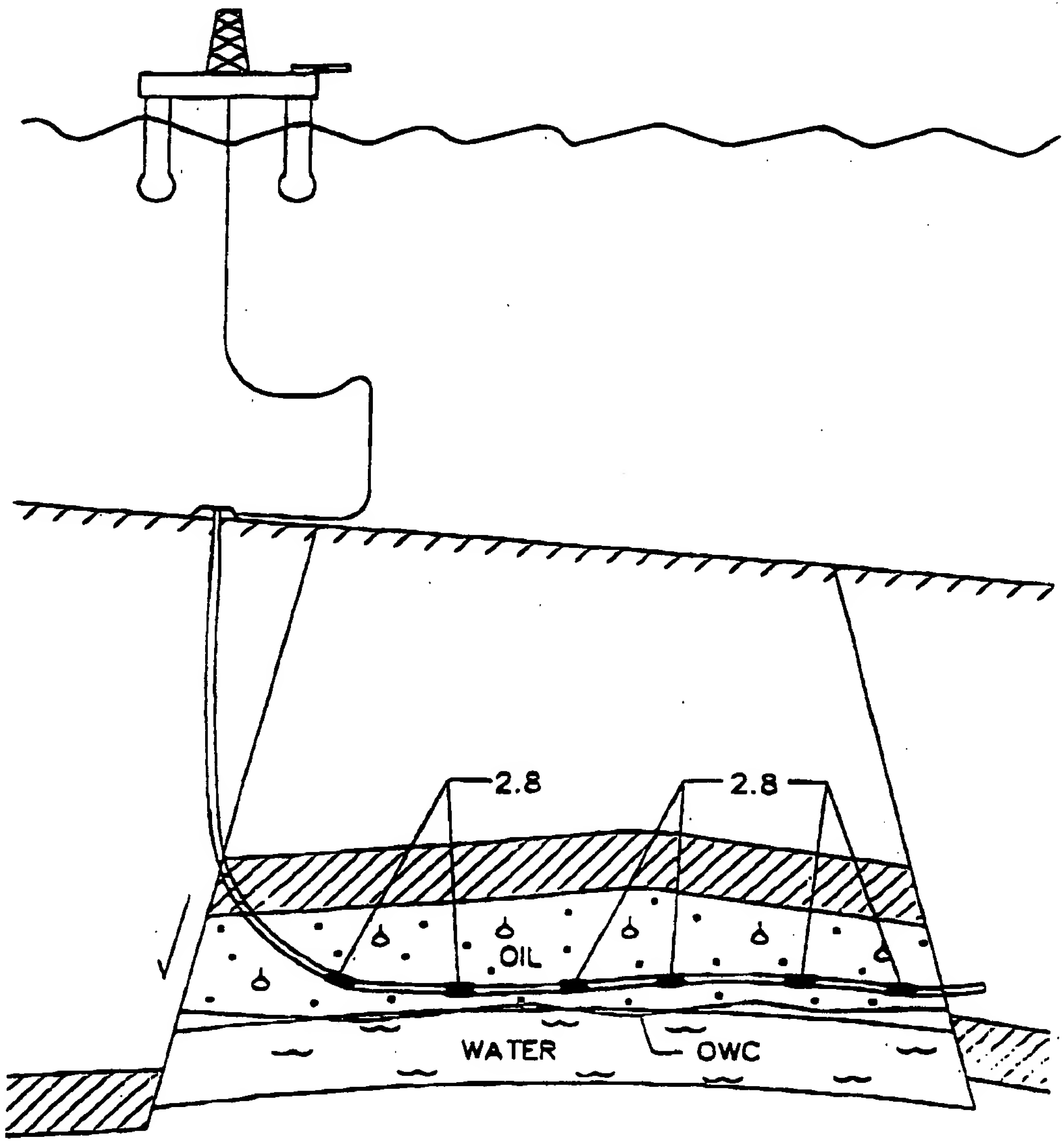

FIG. 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/NO 99/00202

A. CLASSIFICATION OF SUBJECT MATTER

IPC6: G01V 3/30

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC6: G01V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5233304 A (CHRISTIAN HUBANS), 3 August 1993 (03.08.93), column 1, line 39 - line 68; column 2, line 1 - line 33, figure 2, abstract --	1-20
A	US 5860483 A (SVEN O. HAVIG), 19 January 1999 (19.01.99), column 1, line 65 - line 67; column 2, line 1 - line 41; column 5, line 3 - line 29, figure 1, abstract --	1-20
A	US 5363094 A (PHILIPPE STARON ET AL.), 8 November 1994 (08.11.94), column 3, line 48 - line 68; column 4, line 1 - line 68; column 5, line 1 - line 54, figure 1 --	1-20

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" erlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance: the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance: the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
23 November 1999	10 -12- 1999

Name and mailing address of the ISA/	Authorized officer
Swedish Patent Office Box 5055, S-102 42 STOCKHOLM	Tomas Erlandsson/Ae

INTERNATIONAL SEARCH REPORT

International application No.
PCT/NO 99/00202

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 9737103 A1 (SHELL INTERNATIONALE RESEARCH MAATSCHAPPIJ B.V.), 9 October 1997 (09.10.97), figure 1, abstract --	1-20
A	US 5303773 A (JEAN CZERNICHOW ET AL.), 19 April 1994 (19.04.94), figure 1, abstract -- --------	1-20

INTERNATIONAL SEARCH REPORT

Information on patent family members

02/11/99

International application No.
PCT/NO 99/00202

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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		AU 644818 B	23/12/93
		AU 6581190 A	23/05/91
		CA 2029938 A	16/05/91
		DE 69004059 D	00/00/00
		DK 433110 T	07/03/94
		EP 0433110 A,B	19/06/91
		FR 2654521 A,B	17/05/91
		NO 176334 B,C	05/12/94
		OA 9271 A	31/08/92
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		NO 305573 B	21/06/99